9950-637

DRL 133

DOE/JPL-955699-81/05

Distribution Category UC-63

# EQUIPMENT DEVELOPMENT FOR AUTOMATED ASSEMBLY OF SOLAR MODULES

Final Report

In Reference To:

JPL Contract No. 955699

Prepared For:

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103



January 1982

MB-R-81/14

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PREPARED BY: JOHN J. HAGERTY

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The JPL Flat-Plate Solar Array Project is sponsored by the U. S. Department of Energy and forms a part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE.

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## ABSTRACT

Prototype equipment was developed which allows for totally automated assembly in the three major areas of module manufacture: cell stringing, encapsulant layup and cure and edge sealing.

The equipment is designed to be used in conjunction with a standard Unimate 2000B industrial robot although the design is adaptable to other transport systems.

Key words: photovoltaics, automated assembly, robotic assembly, cell stringing, lamination, edge sealing.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

## LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

## 1.0 INTRODUCTION

This is the final report of JPL Contract No. 955699. It is a direct follow-on to JPL Contract No. 954882 and therefore makes some references to it. For the benefit of readers unfamiliar with that project, a description of the hardware developed is included.

The scope of work under this contract includes making improvements to the hardware developed on contract 954882 (to reduce cycle time and improve the system capability) and developing new hardware to allow the robot to carry out the next steps in module manufacture.

Work was broken into five phases. The first phase was to modify existing hardware and controlling computer software to: 1) improve cell-to-cell placement accuracy, 2) improve the solder joint while reducing the amount of solder and flux "smear" on the cell's surface, and 3) reduce the system cycle time to 10 seconds.

The second phase involves expanding the existing system's capabilities to be able to reject broken cells and make post-solder electrical tests.

Phase 3 involves developing new hardware to allow for the automated encapsulation of solar modules. This involves three discrete pieces of hardware: 1) a vacuum platen end effector for the robot which allows it to pick up the 1'x4' array of 35 inter-connected cells. With this, it can also pick up the cover glass and completed module. 2) a lamination layup machine which cuts the various encapsulation components from roll storage and positions them for encapsulation, and 3) an automated encapsulation chamber which interfaces with the above two and applies the heat and vacuum to cure the encapsulants.

Phase 4 involves the final assembly of the encapsulated array into a framed, edge-sealed module completed for installation. For this we are using MBA's Glass Reinforced Concrete (GRC) in panels such as those developed by MBA for JPL under Contract No. 955281. The GRC panel plays the multiple role of edge frame, substrate and mounting structure. An automated method of applying the edge seal was also developed.

The final phase (5) deals with the fabrication of six 1'x4' electrically active solar modules using the above developed equipment.

To determine the value added cost of these new processes, Format A and Format B data sheets were generated to allow them to be integrated into a standard SAMICS industry. These forms, along with their justifications, are included as Appendix A.

## 2.0 PREVIOUSLY DEVELOPED EQUIPMENT

Contract 954882 was a feasibility demonstration to show that industrial robots (also known as programmable or "soft" automation) could be used to layup and solder together strings of photovoltaic cells. The program included an extensive analysis of various techniques for preparing, positioning and soldering cells. A summary of the analysis is included in that program's final report (document # DOE/JPL-954882-80/21), which is available through National Technical Information Service (NTIS).

Based on the criteria established in this analysis, we arrived at a candidate system for prototype development. The system is shown as an artist's conception in Figure 2-1. For simplicity, only one of the ribbon feed and solder paste dispensing mechanisms are shown. In actuality, however, there are two of each of these since we are using an ARCO Solar cell which has a dual lead configuration.

Our method incorporates a robot end effector, or "hand", which combines an induction heating coil and a compliant vacuum pick up. This scheme of robot operation requires that it interface with a "smart" preparation station. This station must be able to accept standard H bar cassettes of randomly oriented cells, unload the cells, rotate them to the orientation the robot is expecting, apply the proper amount of solder paste in the correct places, measure and cut lengths of interconnect lead, place a stress-relief crimp in the correct place in the lead and do it all with a cycle time less than or equal to that of the robot. The robot then picks up this fully-prepared cell, begins heating it while "in transit", and places the hot cell on top of the exposed, solder-coated leads from

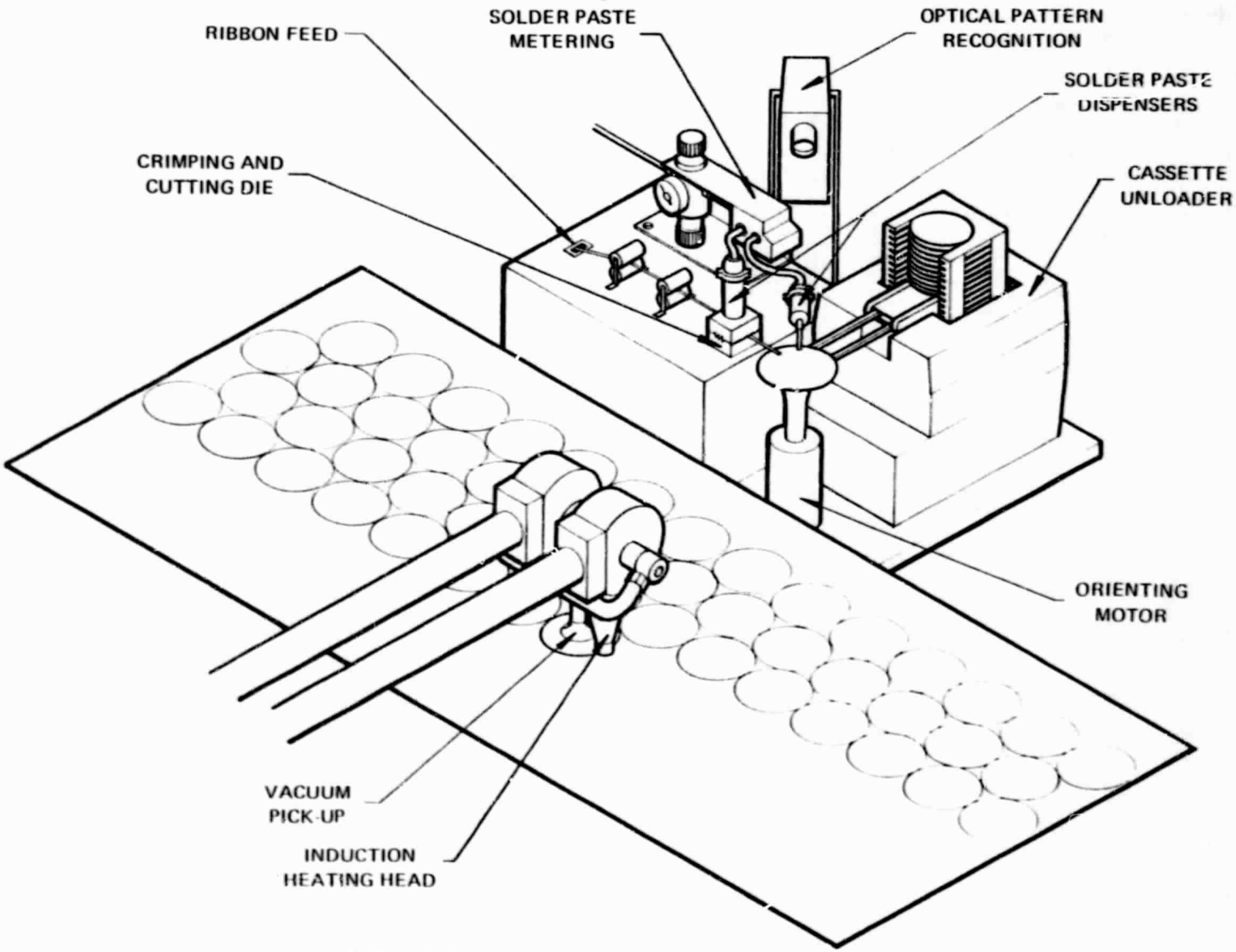


FIGURE 2-1
PREPARATION STATION AND PANEL LAY-UP

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the previous cell completing the connection. A small micro-computer is used to synchronize all of this activity.

## 2.1 Hardware Description and Development

Following is a description of the equipment incorporated into the system. This equipment is divided into mechanical and electrical systems as they were developed separately. Development histories are given only when it is helpful to understanding.

The major mechanical system consists of the preparation station which is further broken down into its various subsystems. The robot end effector also comes under this heading.

### 2.1.1 Preparation Station

The cell preparation station is the major mechanical development of contract 954882. It consists of several individual components each of which will be discussed separately. Figure 2-2 is an overall view of the station.

#### 2.1.1.1 Cassette Unloader

To unload the cells from the standard H bar poly cassettes, we are using a Siltec model 2600A load/unload module. There was only one modification done to the Siltec. As delivered, the cells emerge from the cassette and stop at the edge of the unloader. The unloader was modified to extend the drive belts out approximately 2" to the edge of the vacuum chuck.

#### 2.1.1.2 Vacuum Orientation Chuck

As originally conceived, this was simply a rotating vacuum cup that was attached to the underside of the cell after it was unloaded from the cassette; its sole purpose being to provide rotation for cell orientation. By the time the first prototype had been built, however, its role had been expanded. It was now seen as the platform upon which all of the cell preparation would be performed and it operated in two modes: pressure and vacuum.

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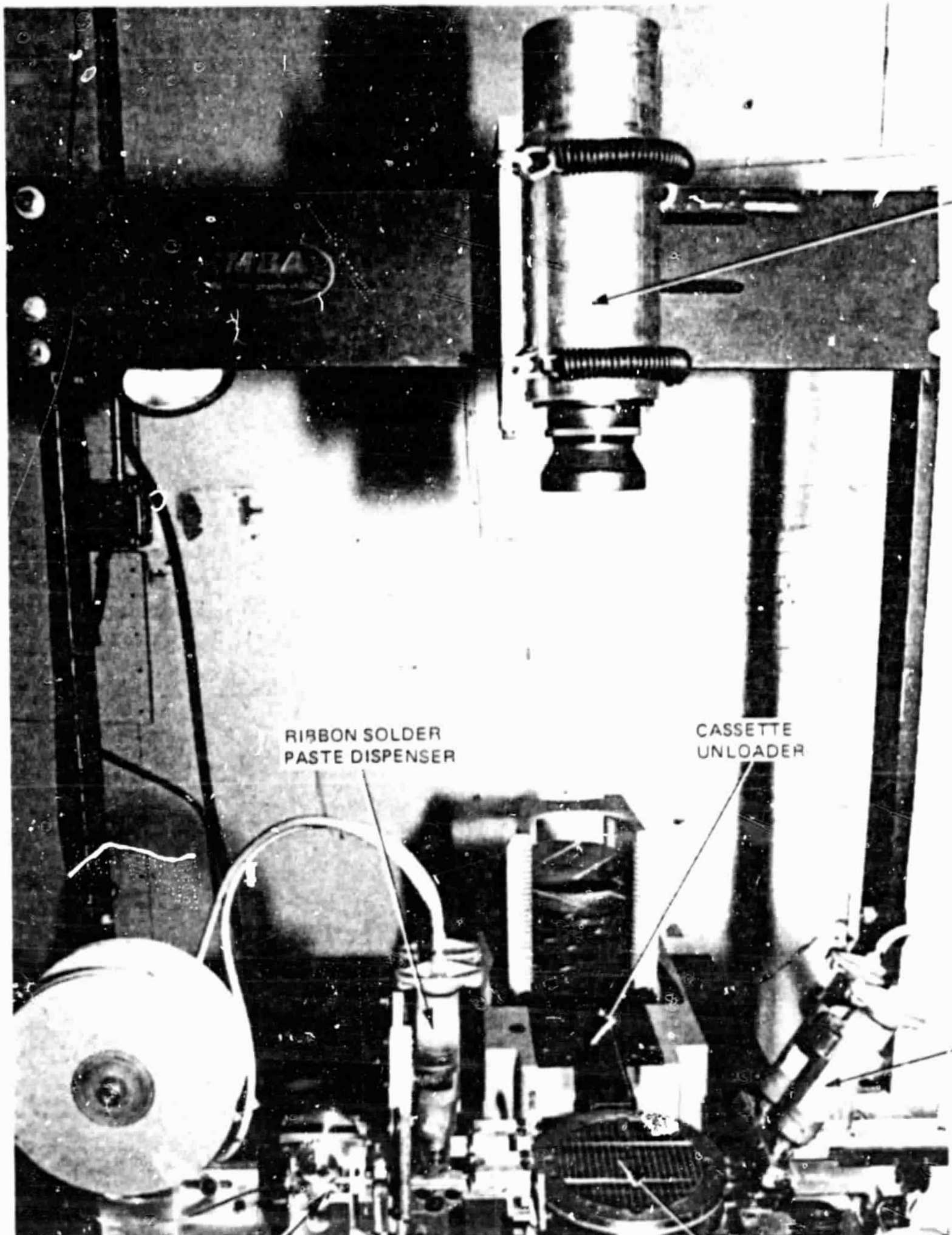


FIGURE 2-2
GENERAL VIEW

The first mode (slight positive pressure) makes the chuck an air table allowing the cell to glide off the unloader's belts without touching the chuck's surface. The pressure also extends the cell locating pins which correctly locate the cell on the chuck regardless of whether or not the cell has a flat (Figure 2-3). The chuck is tilted approximately $5^{\circ}$ from the horizontal to allow the cell to glide "down hill" into the pins. The second mode, vacuum, retracts the pins and clamps the cell to the chuck. It was found, however, that reverting to the first mode (pressure) when releasing the cell caused slight dislocations in cell position as well as re-extending the locating pins which interfered with robot operation. It was decided to add a third mode, ambient pressure, which breaks the vacuum to release the cell, but does not cause cell motion or extend the pins.

The vacuum was originally supplied by a standard shop vacuum pump. A problem was encountered, however, with the high leakage rate around the retractable locating pins. This tended to overwhelm vacuum pump leading to a loss of hold down force. The solution to this problem, was to replace the vacuum pump with a commercial eductor or venturi-type vacuum generator. This device uses a compressed air stream to "generate" a high flow-rate, low grade vacuum. This is precisely what is required in our high leakage rate situation. The main drawback is that the hold down force is only 5-10 lbs., although this is sufficient for our purpose. Early tests of the vacuum chuck showed hold down forces of approximately 70 lbs. but those tests were made before the locating pins were installed. The two big advantages to using the eductor are 1) the vacuum is constant (the vacuum pump would start at very high vacuum levels, approximately 28 inch Hg, but would leak to 0 long before the cell was prepared), and 2) it does away with the external vacuum source requirement simplifying the plumbing and making the station more self sufficient. The only external requirements are a single AC line plug and one shop air connection.

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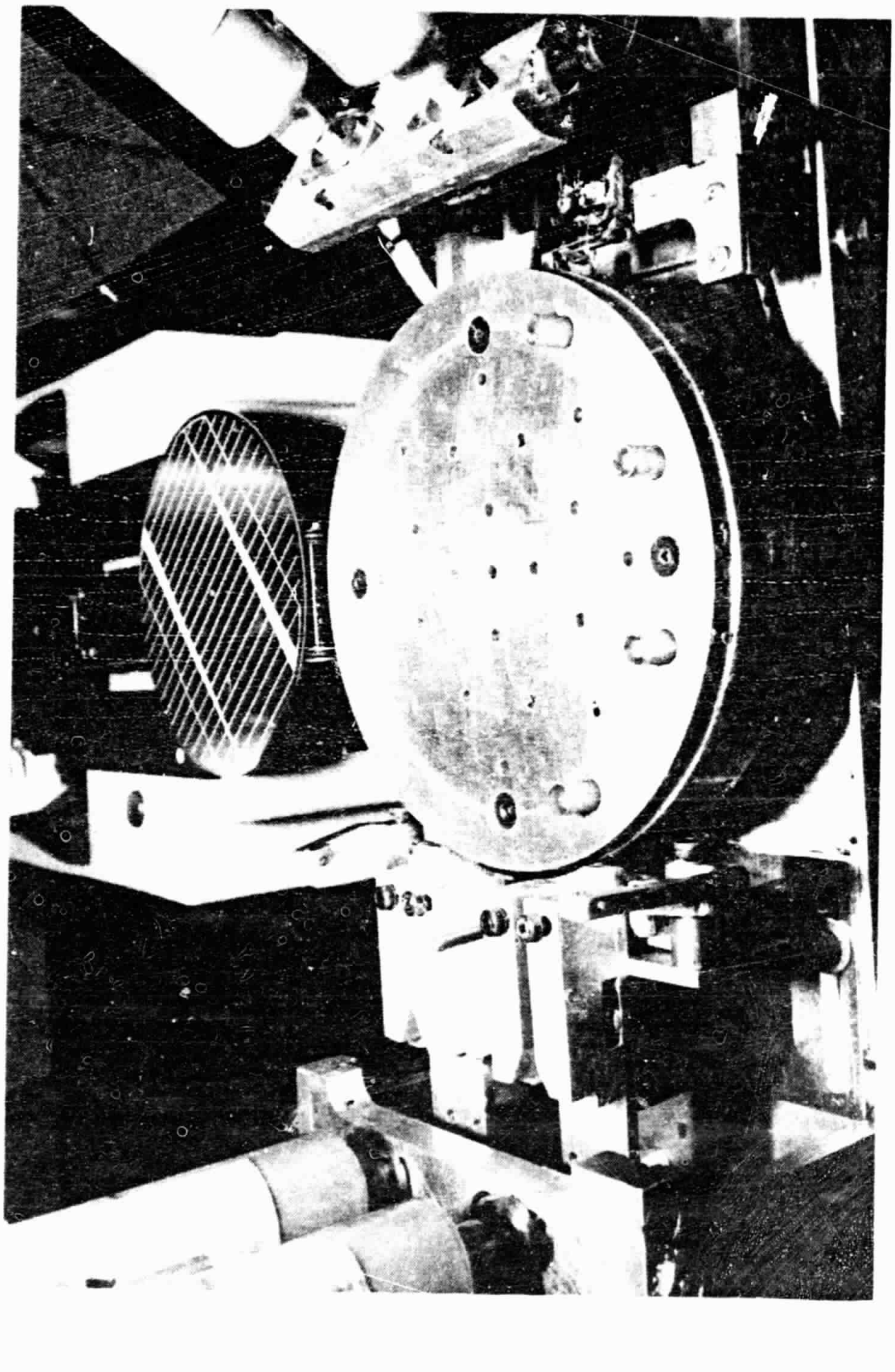

FIGURE 2-3
VACUUM CHUCK WITH EXTENDED PINS

2.1.1.3 Ribbon Feed

The ribbon feed assembly (Figure 2-4) consists of several mechanisms, each of which will be discussed separately.

2.1.1.3.1 Drive Rollers

The original preparation station design (Figure 2-1) had two sets of drive rollers for each interconnect ribbon. It was determined, however, that a single set of rollers is sufficient to feed the ribbon across the entire length of the cell. The rollers have synchronizing gears which insure that the rollers turn without slipping, which would cause the ribbon to curl. The roller assemblies were narrowed from their original size to allow the close (1.625") spacing of two feeds side-by-side which is necessary for the simultaneous application of both leads. Both feeds are driven by a single pin tooth belt located between them.

2.1.1.3.2 Crimp and Cut Mechanisms

These were originally conceived as one device: a crimping die placed close to the cell with a cutting blade on its rear edge. This is sufficient for creating stub leads but in our system the crimp must be placed in the center of an 8" lead. It was determined that these functions would have to be separated. This could be done by leaving the crimp block near the cell and move the cutter back 4". However, with this configuration, when the robot lifted the cell, it would drag 4" of solder paste covered lead through the crimping die. Smearing of the paste and contamination of the die would be unavoidable. Therefore, in the final design we have also moved the crimp die back 4" and placed it behind the cutter. The lead preparation procedure now is to feed out half the lead (approximately 4"), crimp it, then feed the remaining lead while applying solder paste from a dispensing needle located just above the cutter. The cutter is the last device through which the lead must pass. In this way there are no vertical obstructions to the prepared lead when the robot lifts it.

Although each of the leads has its own crimp block, they are operated simultaneously by a single air cylinder through a "T" bar and bell crank linkage. An identical arrangement operates the cutter

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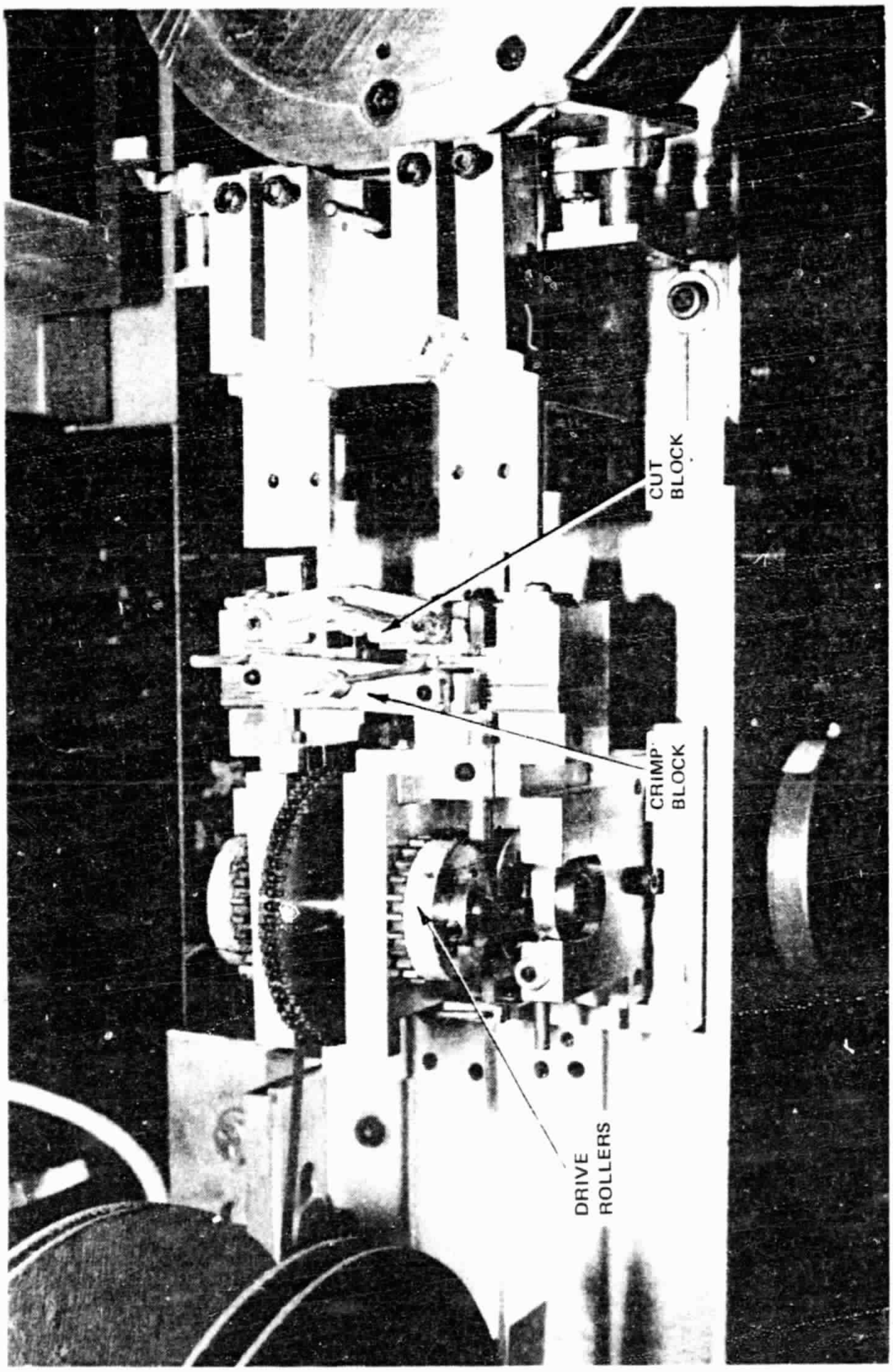


FIGURE 2-4
RIBBON FEED AND FORMING MECHANISM

assemblies.

2.1.1.3.3 Hold Down

Interconnect lead hold downs (Figure 2-5) have been provided in the prototype to prevent lead motions during robot hovering and pickup maneuvers. There are two small, padded arms operated by a single cylinder on a common linkage which clamp the leads to the vacuum chuck's surface. The arms are articulated to swing out as well as up to be completely clear of the lead during lifting by the robot.

2.1.1.4 Solder Paste Dispensing

There are two pair of solder paste dispensers on the preparation station. One pair is mounted on a bridge over the cutter assembly and dispenses paste on the last half of the lead as it emerges from the feed assembly (Figure 2-6). The other pair is mounted on a motor driven ball slide which first extends out over the cell then lays down a bead of solder while retracting (Figure 2-7).

For the fixed solder paste dispensers, the supply tubes are mounted in clips supported by uprights while the needles ride in carriers in the bridge surface. For fast changing of the supply tubes the needles can be removed and inserted in the carriers without disturbing the aiming alignment. Both carriers are spring loaded from the center with adjusting screws on the outside. Once correctly aligned, jam nuts maintain the adjustments. This mechanism is quite flexible as the paste can be easily aimed to fall anywhere on the ribbon. Also, by varying either the air pressure and/or ribbon feed rate, the bead of solder can be made to form dashes (when the solder flow rate is less than ribbon feed rate), solid lines (when the rates are equal) or even swirl, (when the flow rate exceeds the feed rate). Each of the four dispensers has its own in-line pressure regulator.

The original design of the moving solder paste dispenser had the dispensing tips mounted on the end of a cantilevered screw drive with a single guide rod on the side. This lightweight mechanism was in-

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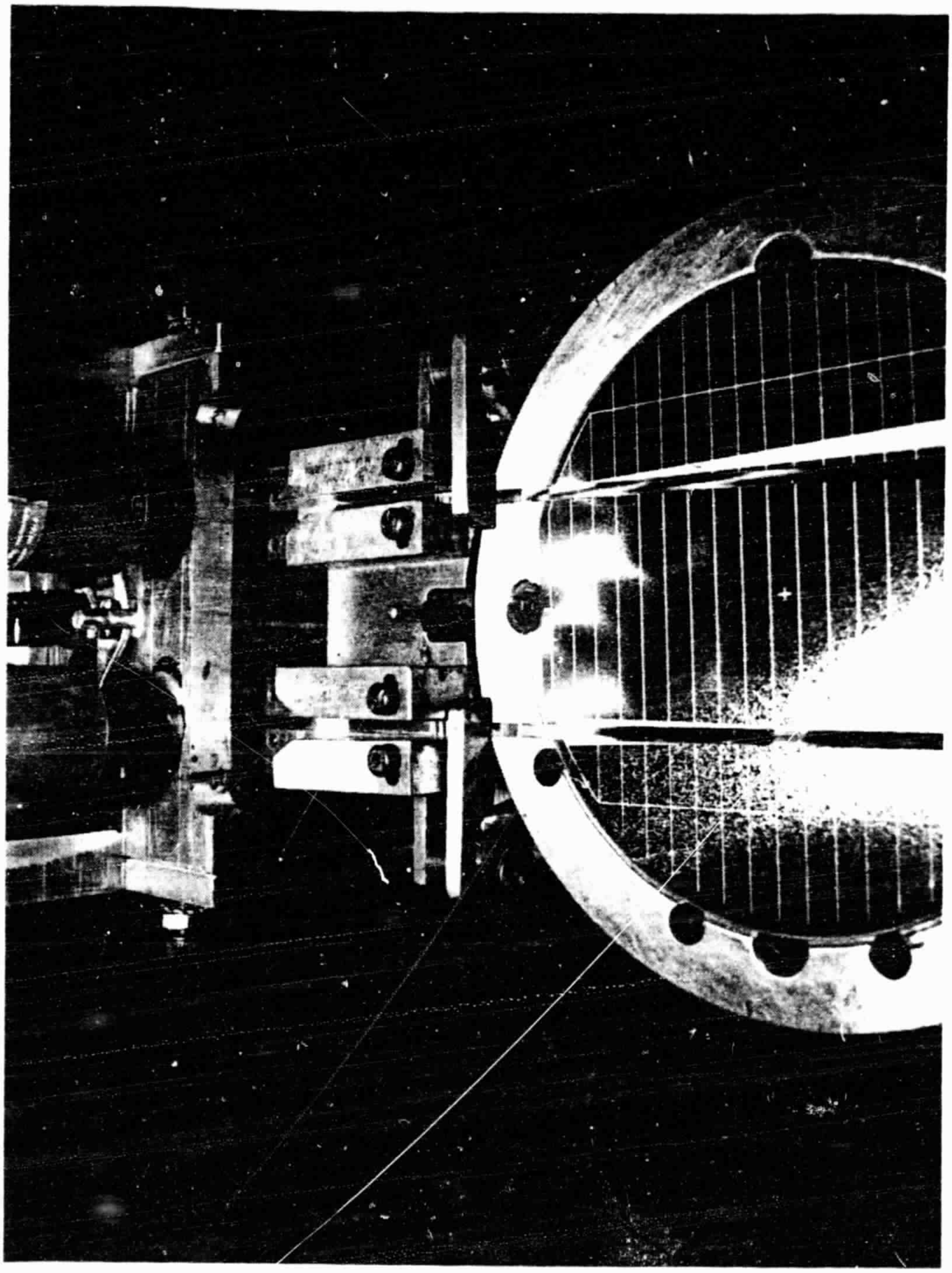

FIGURE 2-5
RIBBON HOLD DOWN

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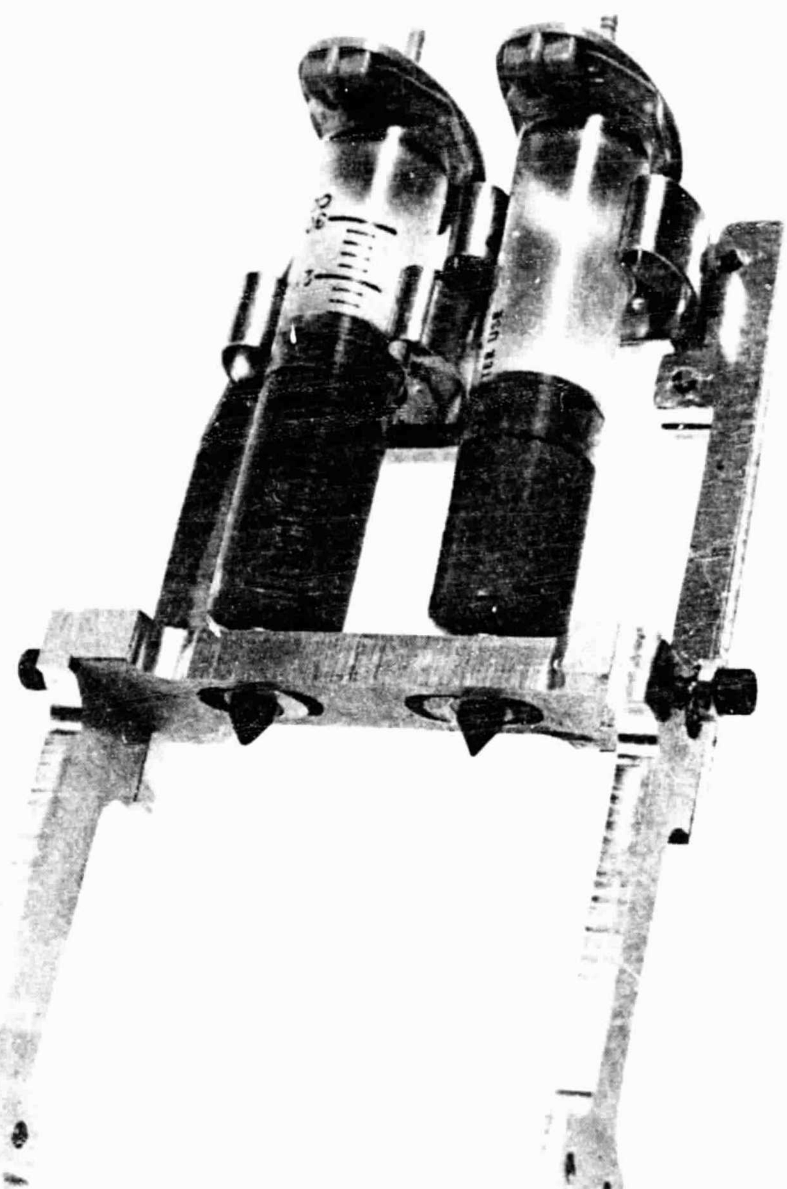

FIGURE 2-6
SOLDER PASTE DISPENSING BRIDGE

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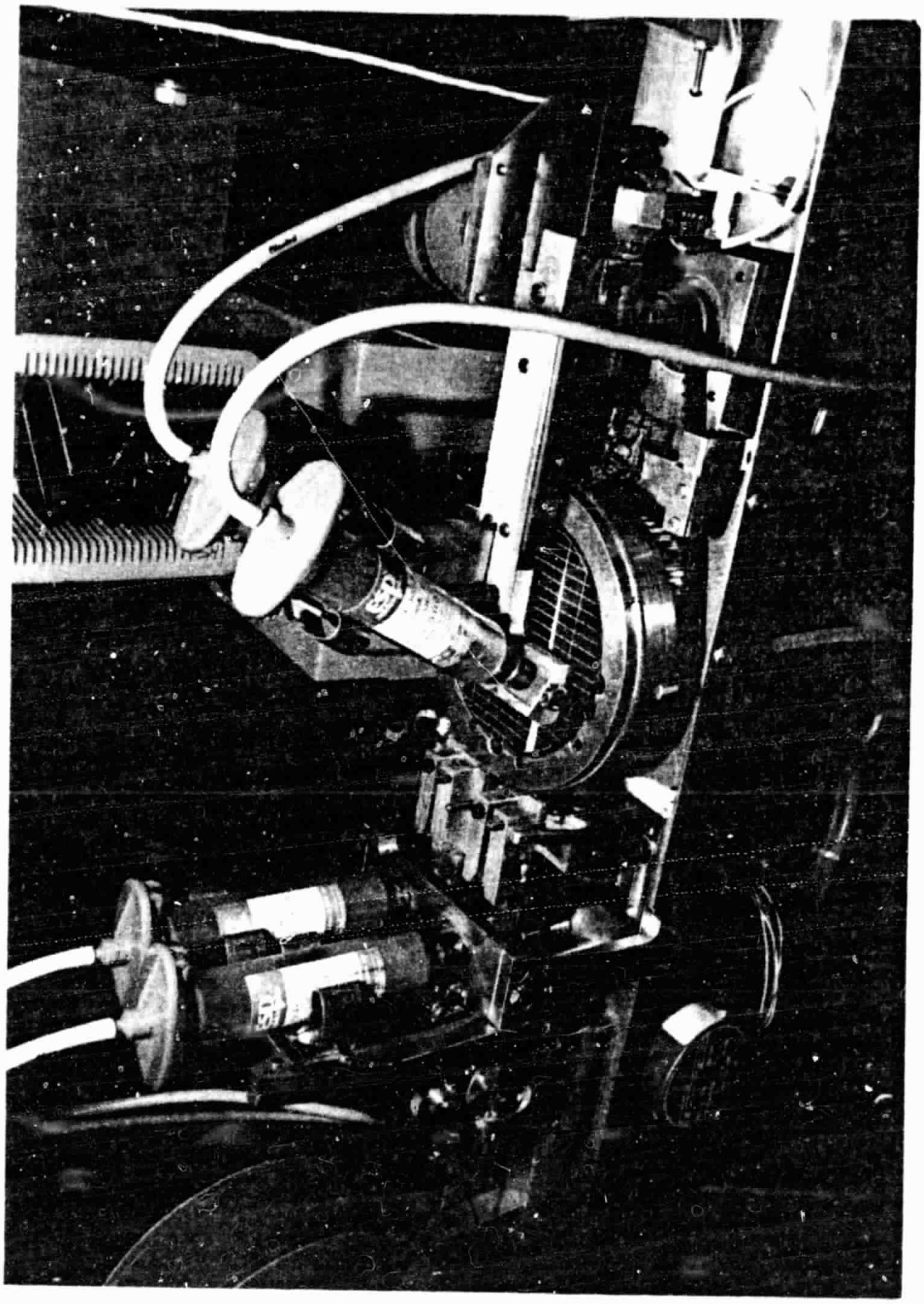

FIGURE 2-7
SOLDER PASTE DISPENSER

adequate for supporting two 30cc paste reservoirs. In addition, it was slow (over 12 sec. cycle time), mechanically inefficient (the losses in the screw drive causes the motor to stall occasionally) and inaccurate due to excessive backlash and bearing slop when fully extended (which caused binding further increasing the load to the motor). It was replaced by a rack and pinion drive attached to a commercial ball slide. The ball slide has a much larger load capacity than the screw drive and can operate at much higher speeds. Other advantages to the ball slide are much higher mechanical efficiency (approximately 90% compared to 40%) and much greater tracking accuracy. The total sideways deviation is only 0.005" at full extension compared to more than 0.1" for the screw drive. (Note: contact pad width is 0.1"). For robot clearance purposes, the supply tubes are laid back at approximately $15^{\circ}$ from the vertical. The needles also ride in carriers and an aiming device identical to that of the fixed dispensers is used.

#### 2.1.1.5 Optical Orientation

The optical sensor consists of a lens which focuses an image of the cell onto a mask, behind which is a photovoltaic cell. (See Figure 2-8). When the cell is in the proper orientation, the image of the bright metallization pattern is admitted by the mask (actually a series of blocking slits) raising the output of the photocell. The phenomenon involved is simply the greater reflectivity of the silver in the metallization pattern compared to the adjacent silicon surface.

Although simple in design, the sensor works flawlessly. When coupled with the correct computer program and control electronics, it will consistently orient cells to within $1^{\circ}$, which is the positional limit of our turntable.

A necessary addition is that of an auxiliary light source. This is to compensate for the unpredictable nature of the ambient light in the area that the station is to be located. A moving person or object (such as the robot) casting a shadow on the cell during orientation could degrade the signal sufficiently to cause problems.

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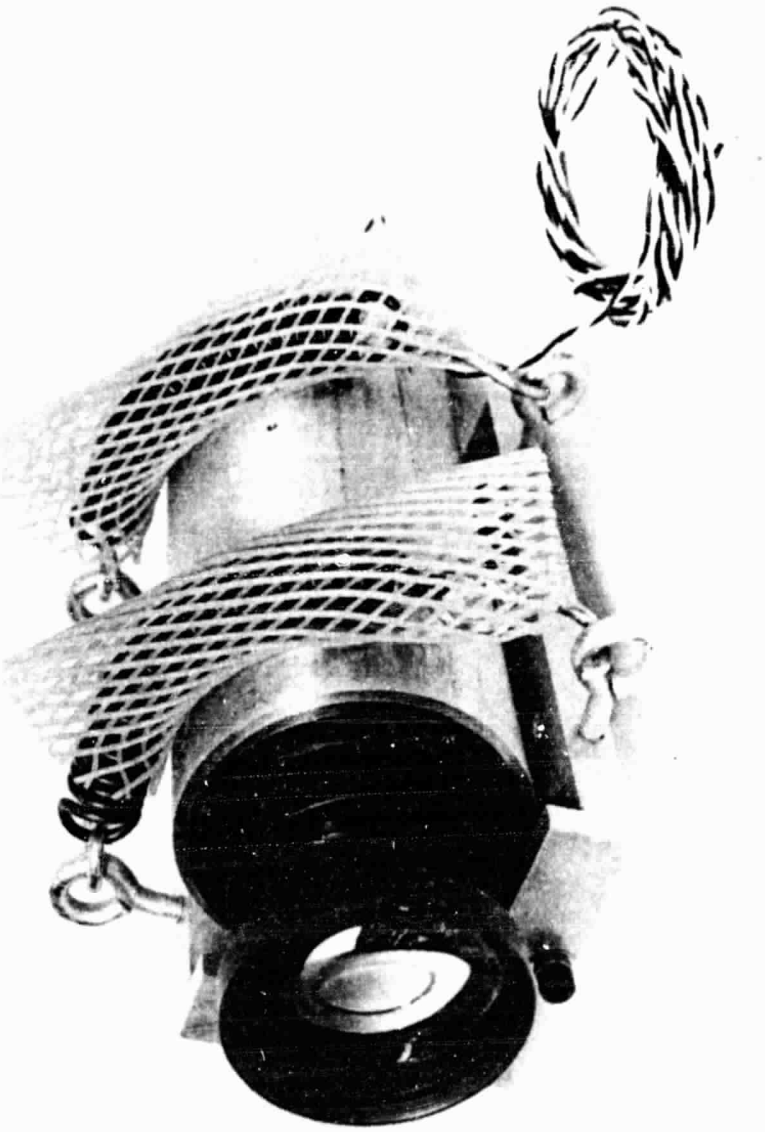

FIGURE 2-8
OPTICAL ORIENTATION SENSOR

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The crystalline nature of the cell's surface causes secondary reflections at about 45$^{o}$ from the vertical. If the light source is placed at or near this angle it causes a contrast reversal as seen by the sensor, i.e., the metallization appears as a dark pattern against a bright surface. This is easily prevented by careful lamp positioning. Another problem is that there is a 60 Hz "hum" superimposed on all lamps that use line current, even incandescents. Experiments with various lamps showed regular room lamps with low temperature filaments to be the worst. In some cases the amplitude change due to the hum was greater than that which we were trying to measure when scanning the cell. It was found that higher temperature filaments (higher wattage bulbs) suffered less from this problem so we are using a 600 W movie illumination lamp and reflector as a light source. A better solution for a production machine would be to use a focused DC lamp of much lower wattage as 600 W is five to ten times more power than necessary to make the sensor work.

### 2.1.2 End Effector Development

Effort on end effector design was concentrated in two areas: Robot feasibility studies with a resistance-heating type bonder and experimentation with various induction coil configurations leading to the end effector design.

#### 2.1.2.1 Resistance Heating End Effector

A series of tests were performed with the end effector shown in Figure 2-9. It consists of two spring loaded carbon electrodes beside a centrally mounted vacuum pick up. It works by placing one electrode on the lead and the other on the cell's surface thus forcing the current to pass through the solder joint. By using a fairly high current (≈30A)* intense local heating was achieved. This produced excellent bonds to either side of the cell with a fairly short (≈ 1 sec.) bond time. However, this was just a feasibility test. The end effector as-tested could only make

* Surprisingly, tests performed before and after bonding showed no degradation of cell output regardless of which way the current flowed.

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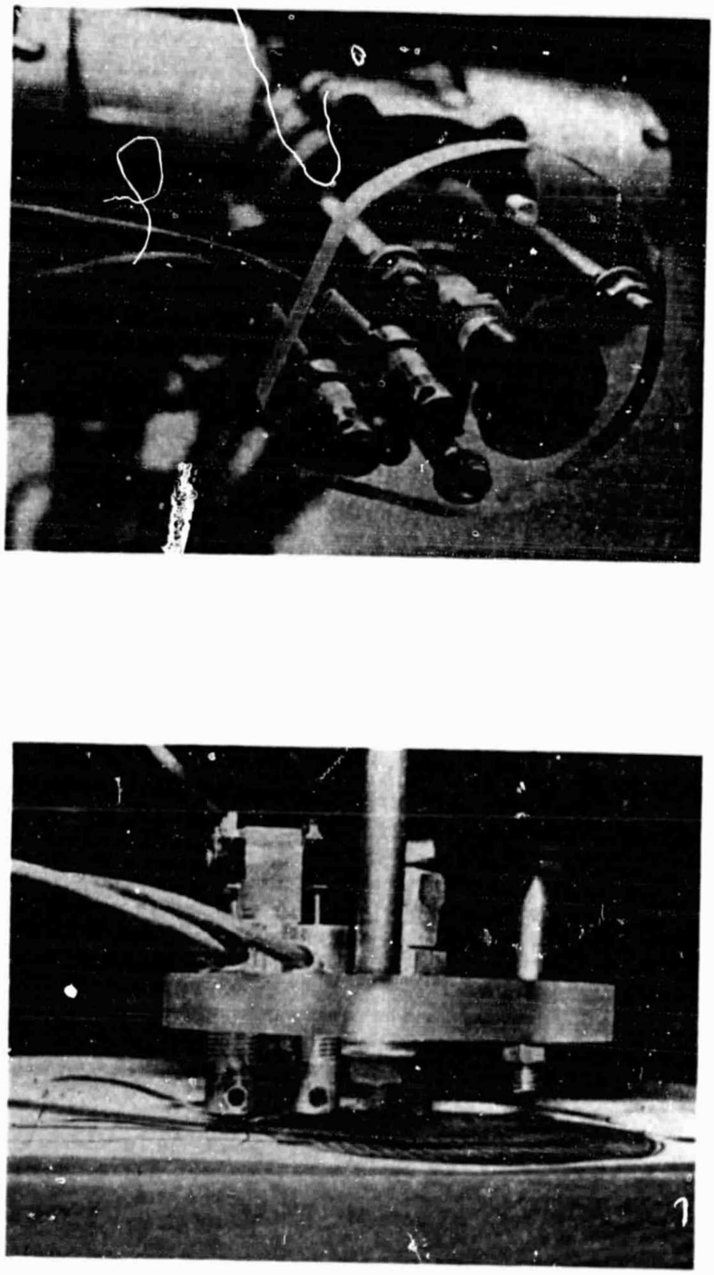

FIGURE 2-9
RESISTANCE HEATING END EFFECTOR

short (<1") bonds and required the high precision positioning of electrodes.

2.1.2.2 Induction Heating End Effector

2.1.2.2.1 Design

For an induction heating power source we used a Taylor-Winfield Model 300 A generator. This unit produces 2.5 Kw at 450 KHz.

Several different coil shapes were tried, all designed to concentrate the induced currents along the strips of the cell where the leads are attached. It turned out, however, that the coil with the fastest heating was a simple spiral or "pancake" coil. Shown in Figure 2-10 is the coil used in the final end effector. The coil is made from ½" thinwall square section tubing (a more efficient RF radiator than round) and measures 4" in diameter.

Figure 2-11 shows the final end effector as mounted on the robot. It consists of the coil described above encapsulated in silicon RTV. The main body is formed of Plexiglass (the material also used in the resistance heat end effector) into which the encapsulated coil is bonded. This is then mounted on a stand-off made of Delrin to remove it from the steel in the robot to prevent any loss of RF energy. At the top of the stand-off is a Plexiglas flange drilled to match the robot's mounting flange. This makes the entire inside of the stand-off a vacuum chamber. Small holes molded in a matrix between the windings of the coil form the vacuum pick up. The encapsulant is thin towards the bottom to get the coil as close as possible to the cell (necessary for fast, even heating) and thick on top to act as a compliant coupling to compensate for robot positioning tolerances.

2.1.2.2.2 Testing and Modifications

The first end effector built to these specifications was tested and its performance was quite satisfactory. There was a problem, however, with uneven heating. This was due to the plane of the coil being non-parallel to the plane of the surface of the pottant where the cell is attached during heating. Where the coil was near the surface there was a hot spot. Where

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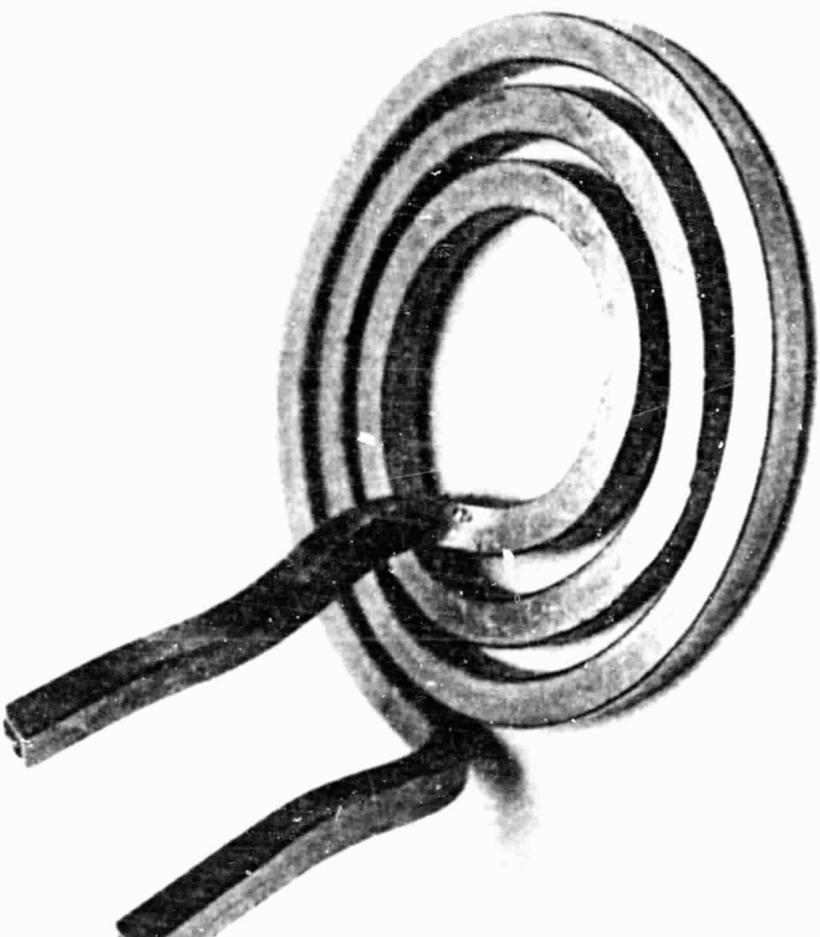

FIGURE 2-10
END EFFECTOR COIL

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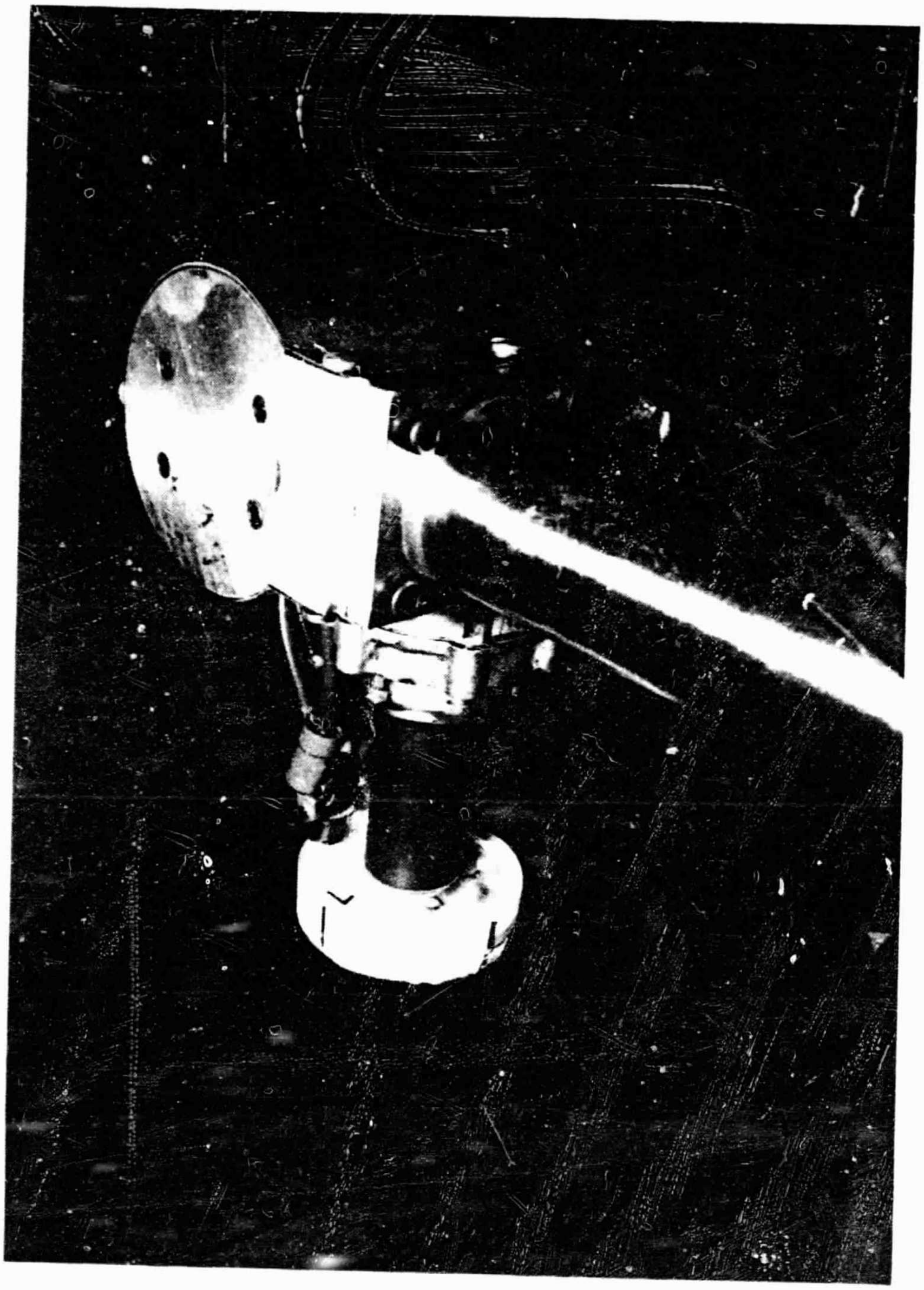

FIGURE 2-11
END EFFECTOR ON ROBOT

the coil was deeper there was a cold spot.

The coil was carefully broken out of the potting and tested "bare". It proved to be quite efficient (bond time ≈ 3 sec.) with very even heating. This further supported the sensitive nature of coupling (the distance between the coil and workpiece).

With this in mind the coil was re-potted paying very close attention to the coil depth during the molding and machining operations. The coil was left somewhat deeper (about 0.5") than final design specs to leave some margin for experimentation.

There were two areas where the end effector performed better than expected. The vacuum matrix on the pickup surface did an outstanding job. It never failed to achieve the pickup even with broken or partial cells that exposed more than half the vacuum holes to air. This capability is necessary for rejecting broken cells. It must be remembered also that the interconnect ribbon was between the cell and pickup, further reducing the possibility of a good seal. Additionally, no cells were broken by the robot during handling tests, not even very thin (<10 mil) cells with severe "potato chip" warping (although several were broken by human handlers!).

We attribute this performance to two factors. One is the broad surface of the end effector which supports the entire cell rather than just one or two points. The other is that we are using an eductor, identical to the one described in Section 2.1.1.2, as a vacuum source. This low grade vacuum is very gentle on the cells and the high air flow rate makes it quite insensitive to exposed air holes.

The other area in which the end effector excelled was heat resistance. We are using General Electric RTV-11 as a potting compound which has maximum temperature limits of $400^{\circ}F$ for continuous use and $450^{\circ}F$ for short periods. As normal soldering operations take place at $350^{\circ}F$ this is sufficient. However, if the cell is broken or has a crack, the induced eddy currents tend to concentrate along the discontinuity causing extreme local heating to temperature in the neighborhood of $1500^{\circ}F$

(based on color).

Even at these temperatures, nearly four times the design maximum for the material, the RTV did not melt, char or decompose in any manner that would damage future cells. The only damage to the end effector's surface was a dry decomposition of the RTV which ranged from a fine powder to pieces the size of eraser crumbs. Although this caused an erosion of the surface, it did not seem to effect the operation of the end effector.

A problem was encountered of the cells sticking to the end effector after soldering due to the melted flux. To assure positive release of the cell, the robot was re-plumbed to produce a positive air flow out of the end effector during release. This gives the end effector the same three modes as the vacuum chuck: pressure, vacuum and ambient.

## 2.2 Electrical and Control Systems

From the outset it was decided to use digital control in the operation of the preparation station. This technique, which uses a micro computer as a system controller, allows the mechanical design of the station to be simple and straightforward. This is due to the fact that all of the "intelligence" of the system can be built into the micro processor by appropriate programming rather than relying on the elaborate mechanical design of cams and linkages. It also allows the system to be extremely flexible as changes in operating parameters (such as a new cell configuration) can be handled in most cases by simply changing the computer program rather than by a mechanical redesign.

A cost/benefits analysis showed the Radio Shack TRS-80 micro computer system (Figure 2-12) to be the most cost effective solution to these control/processing requirements. The TRS-80 uses a Z-80 micro processor and incorporates a BASIC Language interpreter. The model used has the Level II BASIC (which allows access to the computer's assembly language) and 4K of RAM. This can be expanded to 16K or 32K at modest cost.

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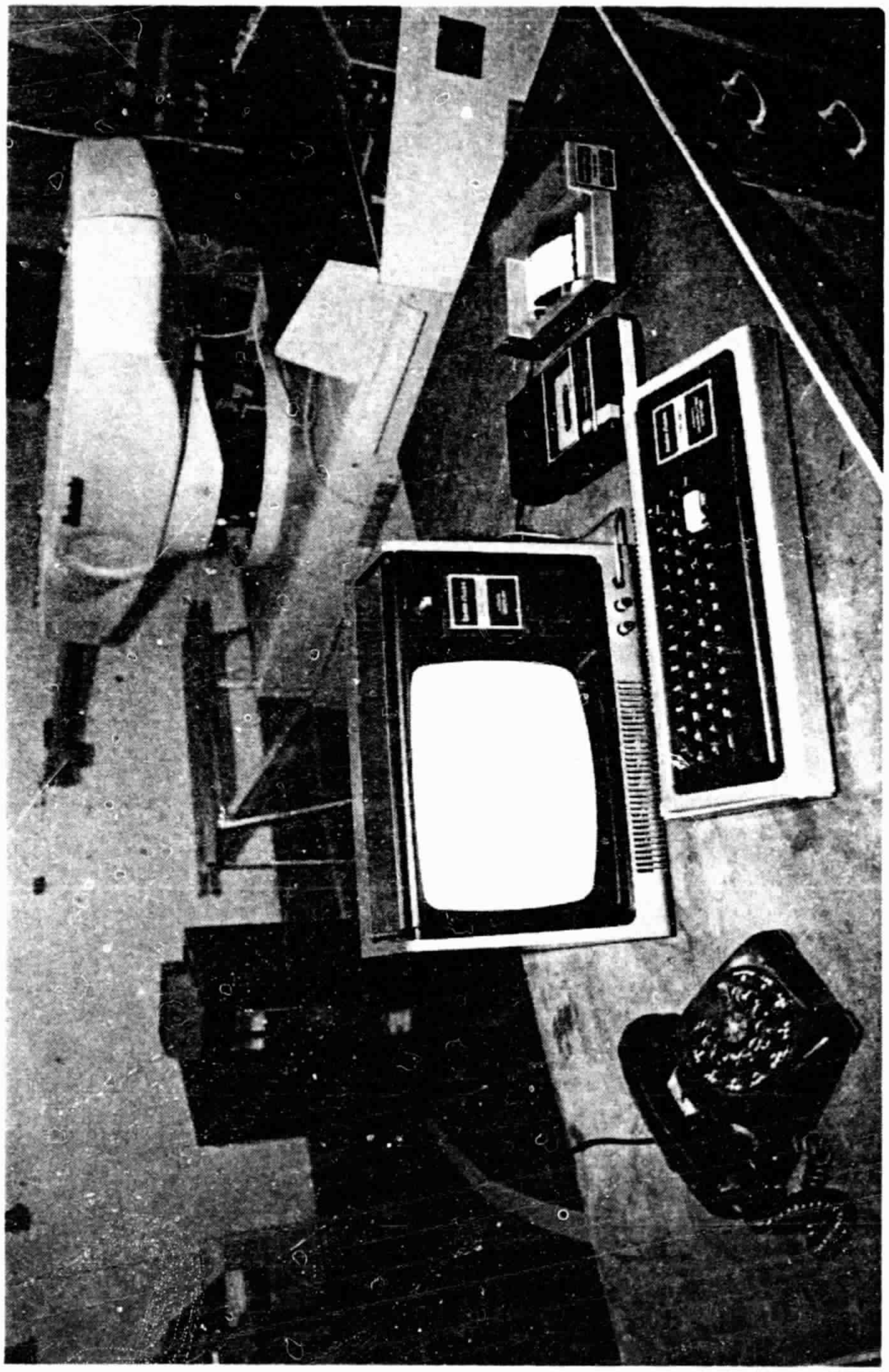

FIGURE 2-12
TRS-80 MICRO COMPUTER

The following discussion is a detailed description of the electronic hardware in the cell preparation station which interfaces the output signals from the computer with the electro/pneumo/mechanical functions of the preparation station.

### 2.2.1 Electronics Package

The electronics package performs three distinct interfacial functions with the TRS-80; mechanical equipment interface, optical orientation sensor interface and Robot interface.

It is necessary to convert the parallel 8 bit data and address information from the computer's output buss into discrete on/off commands for each of the devices controlled by the computer. This is accomplished by an Intel 8255 peripheral interface chip designed for this purpose. A second 8255 is used as an input interface for feedback signals. The 8255's, in turn, interface with the equipment described below. Figure 2-13 is a schematic representation of the data flow within the preparation station.

#### 2.2.1.1 Mechanical Equipment Interface

The output ports from the 8255 cannot be connected directly to the solenoid valves and stepper motors as its current handling capacity is far too low. In order to operate these high current devices, an intermediate driver board must be used. This board contains 22 driver circuits which use Darlington 2N 6055 power transistors to switch the necessary current on and off. In between each driver and the 8255 is a Monsanto 4N33 Optical Isolator. This device (which is essentially an LED connected to a photo transistor) allows information signals to travel without direct electrical connections. In this way large current surges (such as during solenoid valve operation) are prevented from reaching the 8255 thus avoiding potential damage. For the input 8255, the signals pass through a conditioning network consisting of a pair of blocking diodes and fusing resistors. This protects the 8255 in a manner similar to the optical isolators.

#### 2.2.1.2 Optical Orientation Sensor Interface

The optical orientation sensor (Figure 2-8) is an analog

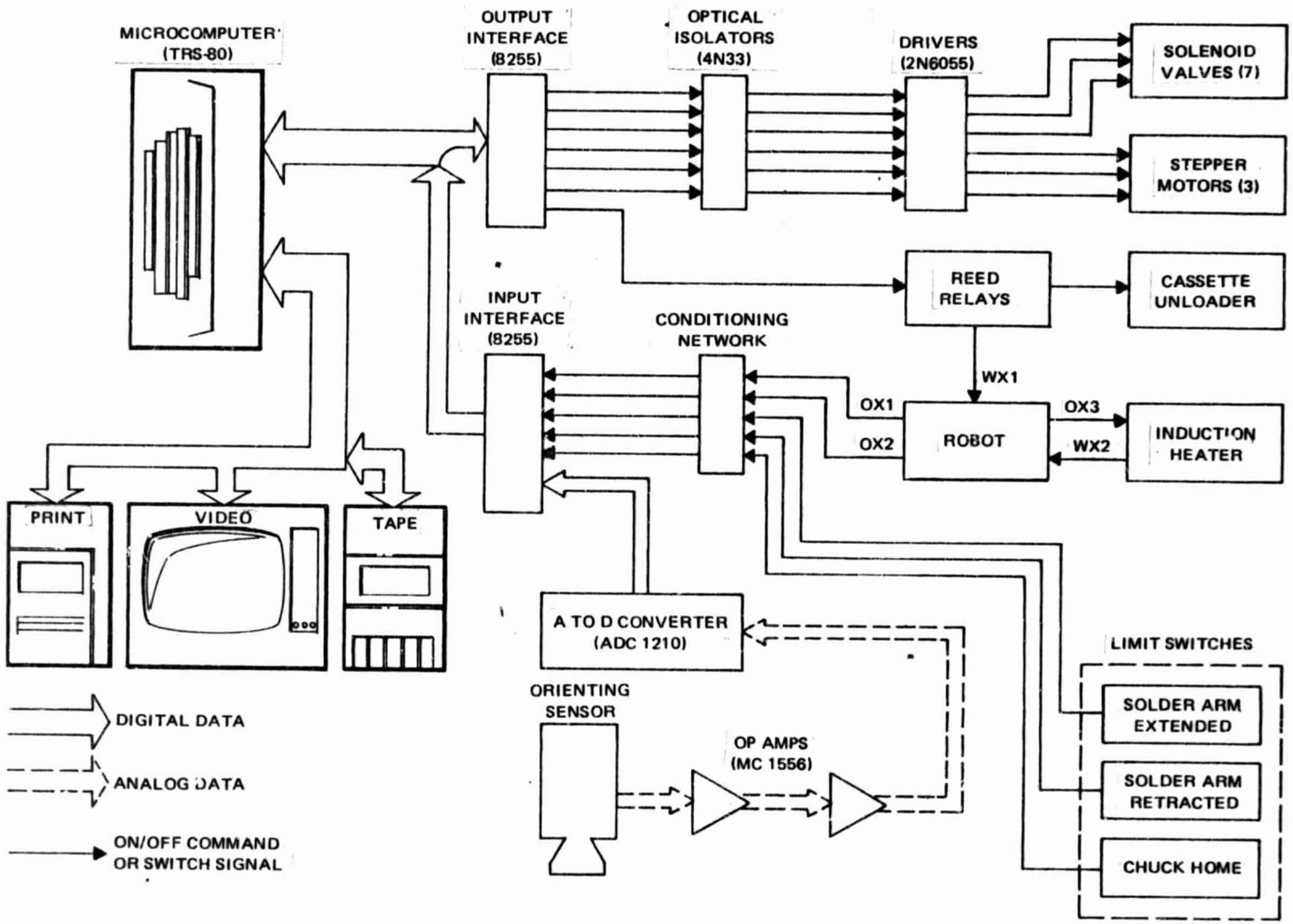


FIGURE 2-13
CELL PREPARATION STATION DATA FLOW

device and its data must be converted to digital form in order to be used by the TRS-80. We used a National Semiconductor ADC 1210 analog to digital converter for this purpose. However, the output from the sensor is so extremely low that considerable amplication (on the order of $10^6$ times) is required. A two stage amplifier using a pair of Motorola MC 1556 op-amps raises the signal to a level detectable by the 1210.

#### 2.2.1.3 Robot Interface

The Unimate Robot was designed for use in industry where hard-wired limit switches are used to signal the completion of external tasks. Due to this "switch closure" logic, the robot is unable to understand the "binary voltage level" logic used by the electronics package. Therefore, we used reed relays, driven by the 8255, to give the robot the "switch closure" it is looking for. This also applies to the Siltec cassette unloader since it also uses "switch closure" to initiate its function.

The robot uses this switch closure two ways: for input and output. When the input or "Wait External" (WX) is programmed into the robot it will wait at that step until it receives a switch closure signifying the completion of the external task. The output or "Operate External" (OX) closes a relay inside the robot presenting a switch closure to whatever external device is being operated.

Being a piece of industrial equipment, the induction heater also uses switch closure to start. As such, it could be operated directly by the TRS-80 via the reed relays. It was decided, however, that since the robot and heater were bound in such a lock-step relationship (the heater cannot start until the robot has picked up the cell and the robot cannot release the cell until the heater has finished) that they would be considered a single unit. The induction heater is controlled only by the robot's internal program. The "heat-on" duration is controlled by the heater's built-in timer.

## 2.2.2 Computer Program

The last portion of the station to be developed was the controlling computer program. This was necessary since it was required that the electro-mechanical portions of the machine be nearly fully developed before the program could be started.

The first step in the computer program's development was to write a single unifying program that would operate all of the functions of the preparation station, signal the robot and Siltec cassette unloader and do it all with the proper sequences and durations. This first program was written in the BASIC computer language for ease of programming. BASIC, however, is quite slow running for this purpose (the cell orientation alone took over 30 sec.) so the next step was to speed up the program. This was done by rewriting some of the subroutines of the program in much faster running assembly language. The first to be rewritten was the cell orientation routine. The assembly language routine cut the orientation time an order of magnitude to just below 3 seconds.

Two other routines were rewritten in assembly language; the ones controlling the ribbon feed and solder paste dispensing arm. The time saved by speeding up these three routines dropped the cell preparation cycle time from 50 sec. (for an all BASIC program) to approximately 15 sec. for the final program.

# 3.0 PHASE ONE: IMPROVEMENTS TO EXISTING SYSTEM

There are three goals in this phase as stated in the introduction: 1) improve placement accuracy, 2) improve solder bond and reduce flux "smear" and 3) reduce system cycle time to 10 sec/cell. Accomplishments on each of these goals are discussed separately.

## 3.1 Improve Placement Accuracy

This is strictly a robot programming problem since the robot does all of the cell handling and transport operations.

The Unimate 2000 was designed for use in medium to heavy industry (such as automobile chassis welding) where accuracy

on the order of a tenth of an inch is acceptable. Its selection for use in the previous contract was based on factors such as reliability, cost and large work area.

However, with this robot, there has always been a problem in laying down cells with a high degree of accuracy. This is mainly because the cells are 4" in diameter and the end effector has a 5" diameter. This means that the cell is completely hidden during the critical final positioning maneuvers. During the previous contract, positioning was achieved by means of fiducial marks scribed on the end effector. These marks were lined up with corresponding marks on the vacuum chuck and with the centerlines on the layup pattern during final positioning. This sort of "dry" programming (without using a cell to check final position) requires that 1) the fiducial marks on the end effector be accurately placed, 2) the end effector be accurately positioned on vacuum chuck during pickup, 3) the cell be well centered on the vacuum chuck and 4) that the end effector be correctly lined up with the pattern centerlines during final positioning. All of these tolerances multiply cumulatively which can severely impact accuracy. Even so, this technique worked well enough to produce an accuracy of $\pm$ 1/4" which was sufficient for the previous contract's requirements.

Current industry standards, however, require a minimum tolerance (i.e. maximum edge-to-edge spacing) of 0.060" between cells. The Unimate 2000, however, has an accuracy limit of only $\pm$ 0.050". Since we are working up against this limit, a more accurate programming technique is required. A simple (in hindsight) yet very effective solution to this problem is the use of a dummy indicator cell. This is a 4" diameter disc with four accurately positioned pointers spaced at $90^\circ$ along the disc's centerlines. Three of the four problems mentioned above are eliminated since the cell's actual centerlines are used for alignment. The only one that must be considered is keeping the indicator cell centered on the chuck. This is slightly more difficult than with a standard cell since the pointers prevent the cell from falling into the chuck's central locating indentation.

Another important, though less dramatic, accuracy improvement has to do with rotational positioning. In any series-connected string of cells, the leads reverse direction as you go from row to row. This requires a nearly $180^{\circ}$ wrist rotation by the robot. Unfortunately, the robot's wrist rotation limit is only $150^{\circ}$ each way from center. With the use of the indicator cell we no longer have to line up the end effector's fiducial marks with the vacuum chuck during pickup. Therefore, we can now "pre-rotate" the wrist $30^{\circ}$ before pickup to give us the extra rotational travel needed.

### 3.2 Improve Solder Bond

We are approaching this task three ways: 1) improving the robot hardware by refining the bonding head (end effector), 2) improving the robot software by incorporating a new soldering technique and 3) using a new method of solder paste dispensing at the preparation station.

#### 3.2.1 Robot End Effector

For even cell heating, it is critical that the cell-to-coil distance be constant over the entire cell area. In previous end effectors, difficulties in holding the coil level during potting prevented this, and even post-potting machining did not fully correct the problem. A new potting technique was used in which the coil was first glued directly to a piece of 1/16" thick silicon rubber sheet. After the glue (a one-part silicon RTV) had set, the coil-and-rubber-sheet assembly was inserted into the plexiglas end effector housing. The outer edge was sealed and the pottant (G.E.RTV 11) was poured through the top. This step also permanently affixed the coil assembly to the housing thus saving two more construction steps (trimming and inserting) that could cause alignment errors. After the pottant had set, the vacuum pickup holes were drilled through the rubber sheet at pre-marked locations.

This new end effector (Figure 3-1) has proven very successful when combined with a new soldering technique which is described next.

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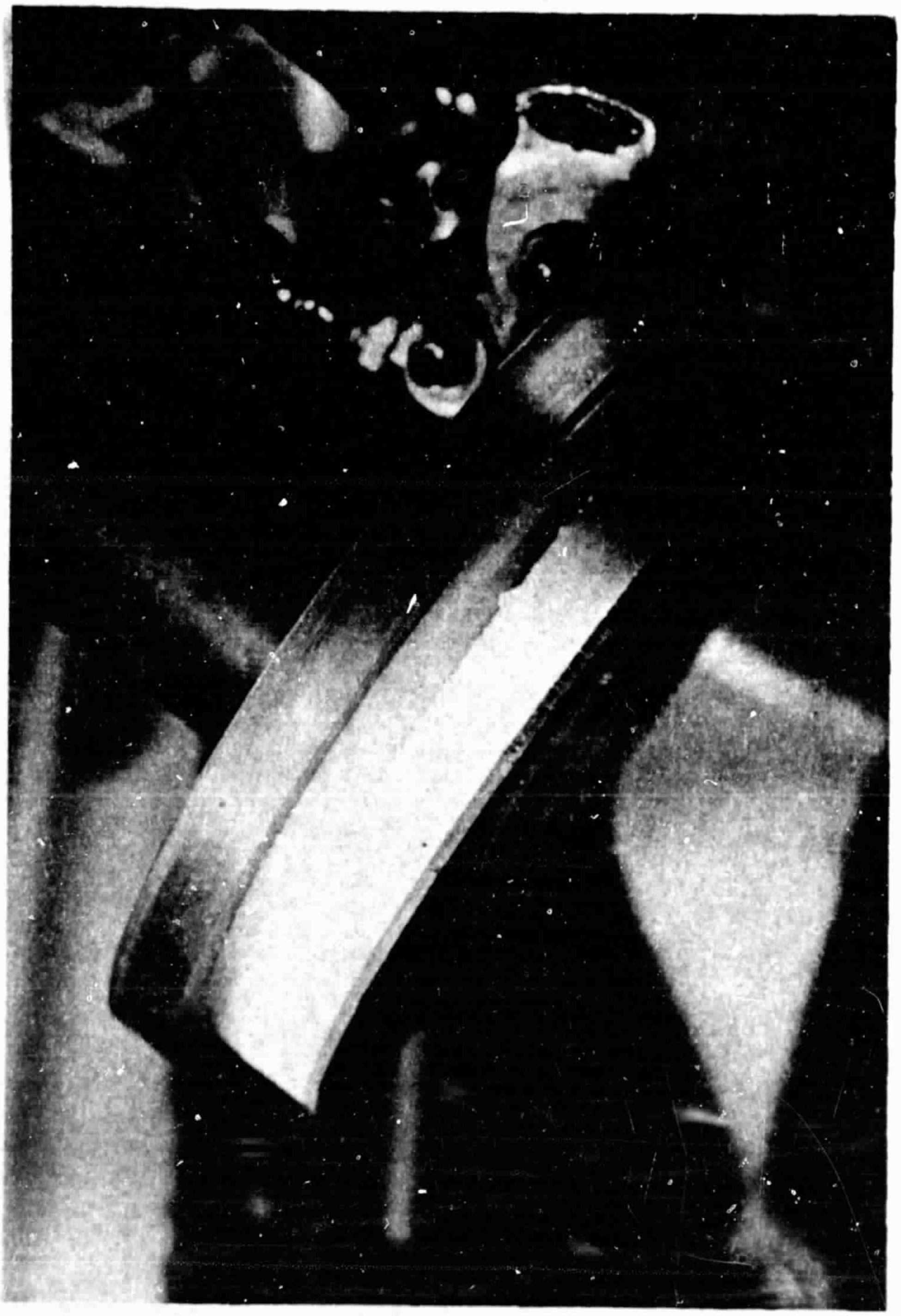

FIGURE 3-1
ROBOT END EFFECTOR SHOWING LAYERED CONSTRUCTION

### 3.2.2 Induction Heat Soldering

There are three problems associated with soldering the leads while the cell is held tightly against the end effector. One is that due to the capillary action from this close proximity the melted flux tends to flow in a thin sheet over a large area of the cell. This "smearing" can be detrimental to cell performance and requires that a cleaning step be added to the manufacturing sequence. Another problem is that the melted flux is quite sticky and causes the cell to adhere to the end effector when the robot tries to release it. The third problem is that the robot must wait for the reflowed solder to cool before releasing the cell to avoid dislocating the leads and causing a "cold" solder joint. We experimented with a new soldering technique that eliminates all three problems.

This new technique starts the same as the old one with the induction heater being turned on just before final positioning to preheat the cell. However, rather than waiting for the solder to reflow and then cool before release, the robot releases the cell immediately and backs off approximately 1/8". Since the cell is released before the solder and flux have melted, there is no capillary action to smear the flux and it stays in a very localized area around the joint (Figure 3-2). The surface tension of the liquid solder pulls the leads down to form an excellent bond. Finally, since the end effector is not in contact with the cell during heating, the robot can leave as soon as the heater turns off allowing the cell to cool on its own. Of course, this 1/8" increase in the coupling (coil-to-cell distance) reduces the RF flux thus increasing the heating time. However, this increase has been found to be less than the old cooling wait time resulting in a net decrease in cycle time. An unexpected side benefit is that the increased coupling also results in a more even heat distribution over the cell.

### 3.2.3 Solder Paste Dispensing Manifold

One area of the preparation station that required upgrading was the mechanism that applied solder paste to the cell's metalization pattern.

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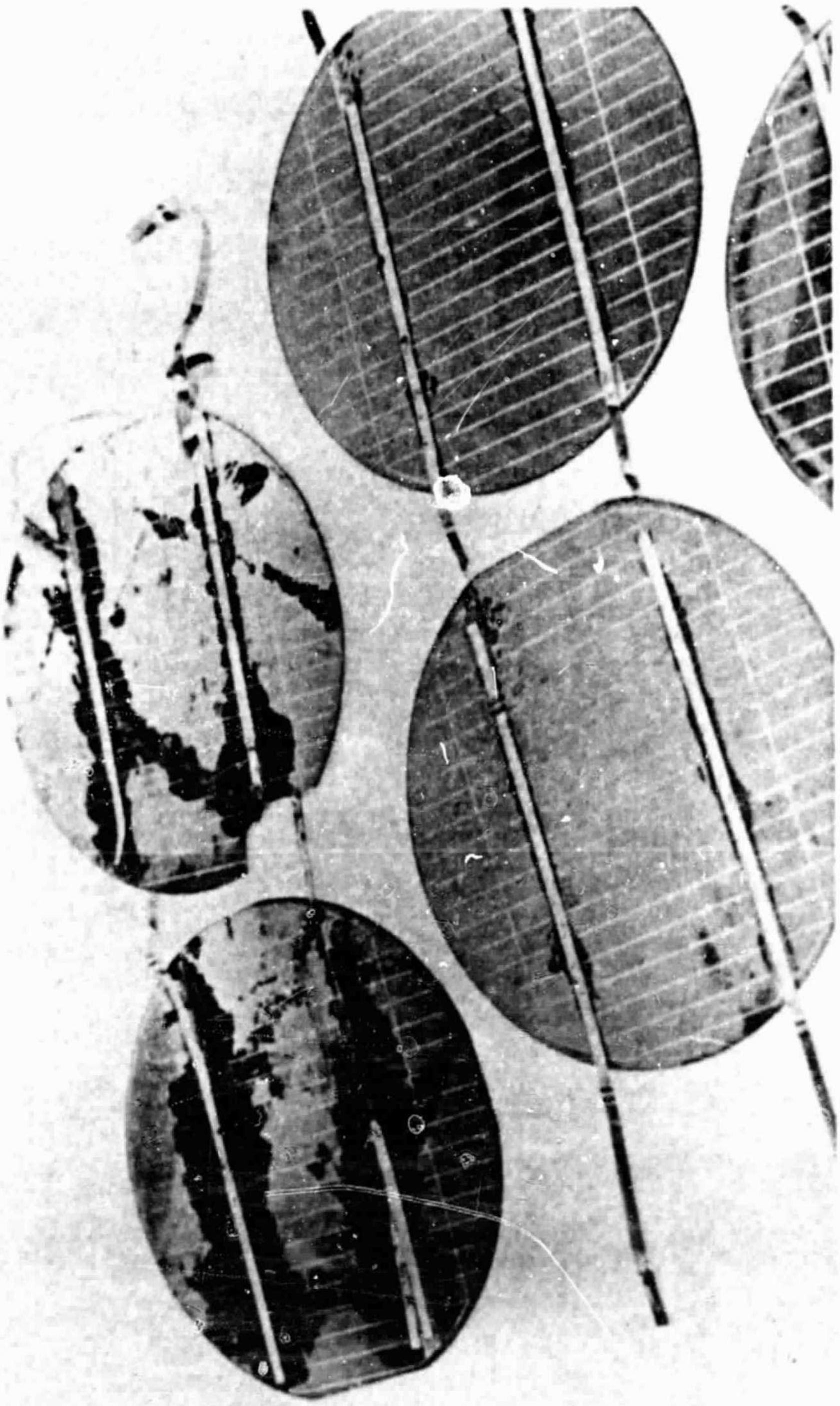

FIGURE 3-2
COMPARISON OF OLD AND NEW SOLDERING TECHNIQUES

In the previous system the paste was dispensed through an 18 gauge needle while the tube was moved in a controlled manner across the cell. The difficulty with this technique lies in producing uniform, continuous beads of solder paste of small diameter (approximately 0.015") using the air-and-piston system.

None of the leading pneumatic dispenser system manufacturers (Tridak, EFD, ASI, etc.) have systems that will produce a bead of high viscosity material using this technique and instead opt for a series of small dots. Following this example, we have built a manifold-type solder paste dispenser of novel design (Figure 3-3). The dispenser consists of two manifolds, one for each lead. Each manifold consists of a hollow, aluminum box in which the solder paste is injected from a single supply cylinder on the top and out through six Tridak low restriction nozzles along the bottom (Figure 3-4). The solder paste cylinder is attached by a leur lock fitting on the manifold lid and supported by a clip holder.

The novelty of this approach has to do with the way it is used in our system. This will be discussed next since it deals with cycle time reduction.

## 3.3 Cycle Time Reduction

The cycle time goal for layup and interconnect on this program is 10 sec/cell. It was determined during the previous program that the preparation station would require only minor modifications to achieve this. Significant gains can be made simply by changing the controlling computer program.

Our preparation station is essentially a serial processing machine, i.e. one cell at a time is run through the complete preparation cycle, as compared with a parallel processor (such as the K&S machine) where several cells at a time move down an assembly line with each work station doing a small part of the preparation.

Figure 3-5 shows the cell preparation and placement cycle of the system as it was at the end of the previous contract. As

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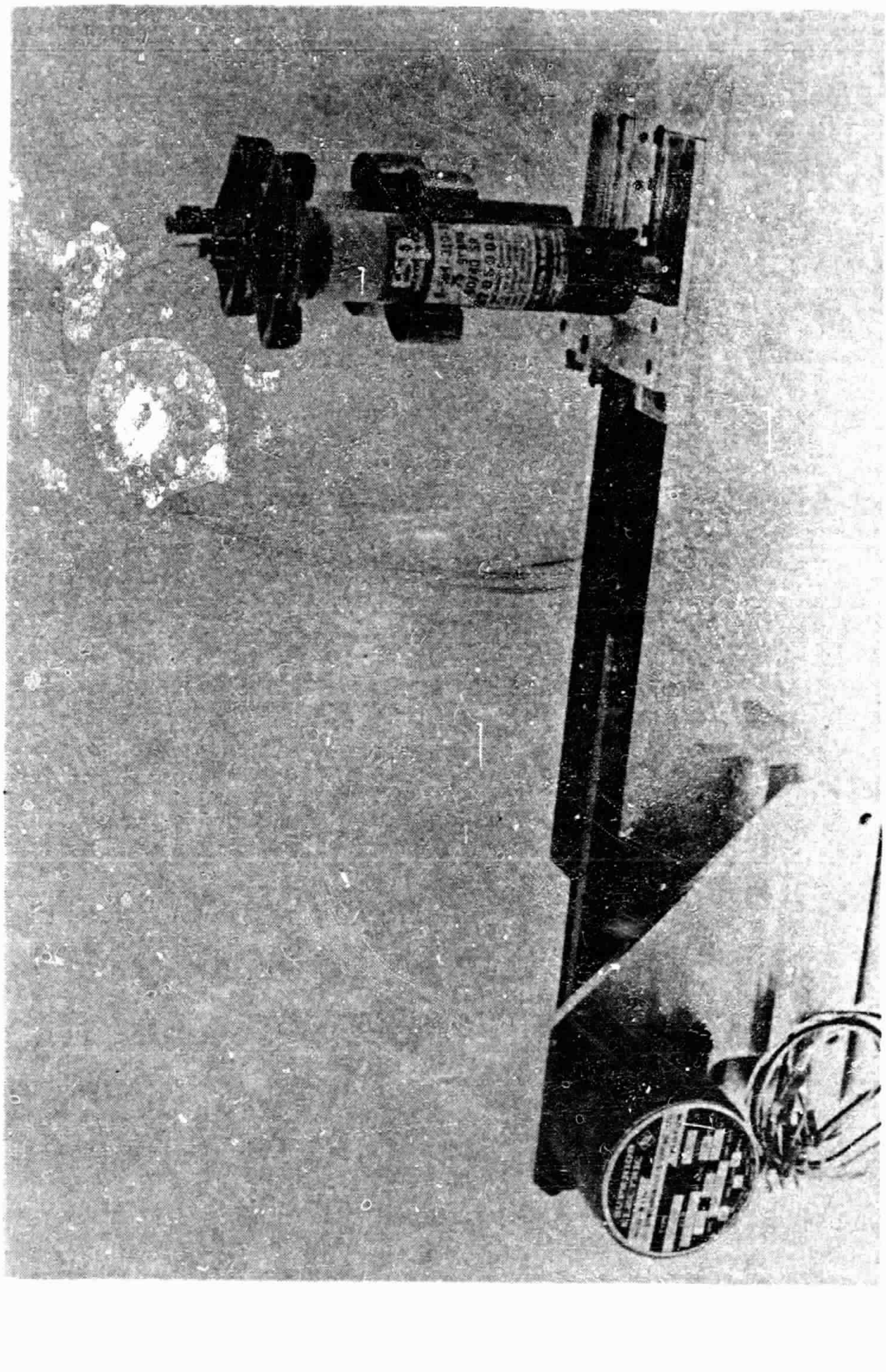

FIGURE 3-3
MANIFOLD-TYPE SOLDER PASTE DISPENSER (Shown Extended)

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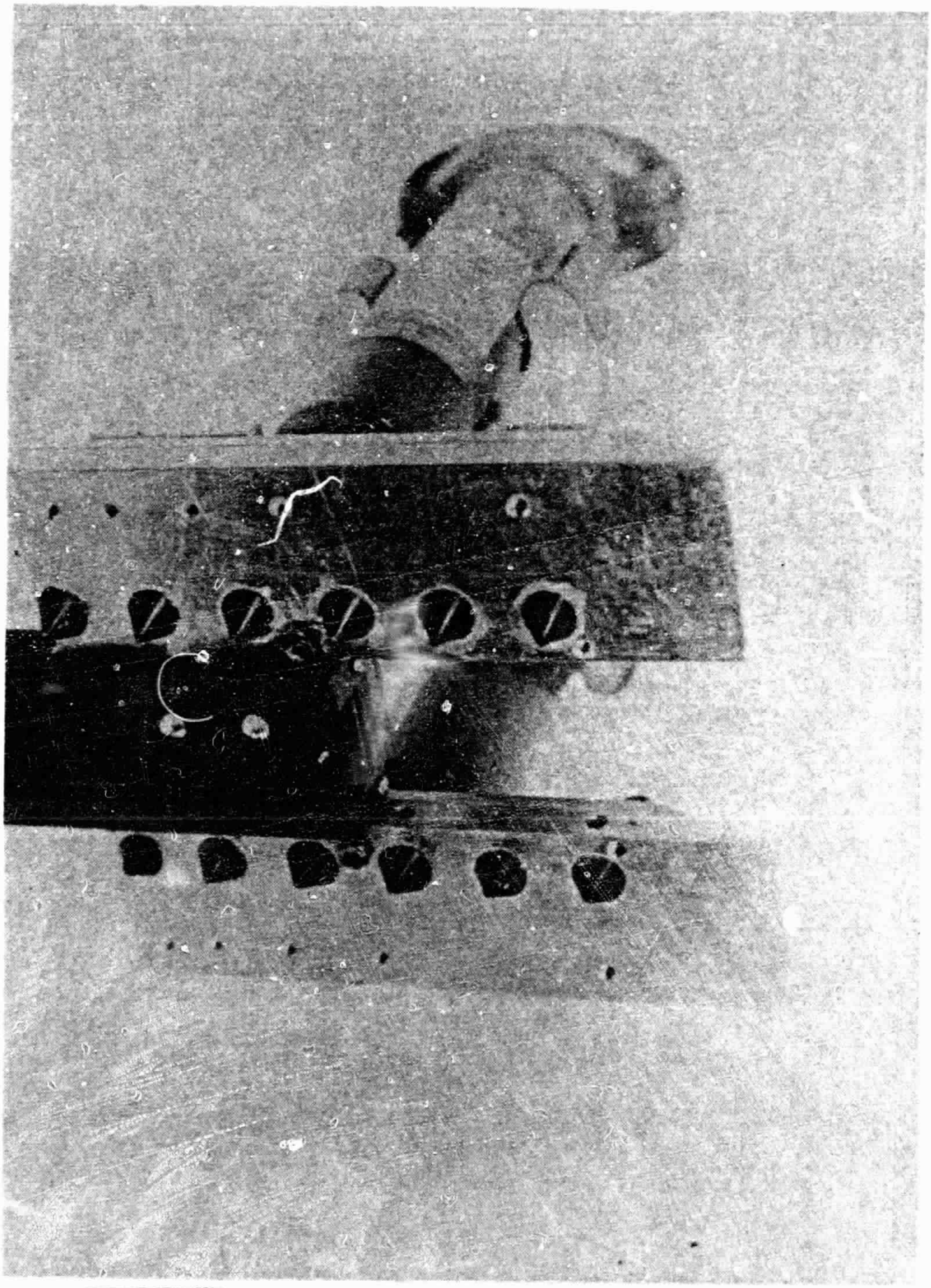

FIGURE 3-4
UNDERSIDE OF PASTE DISPENSING MANIFOLD SHOWING NOZZLES

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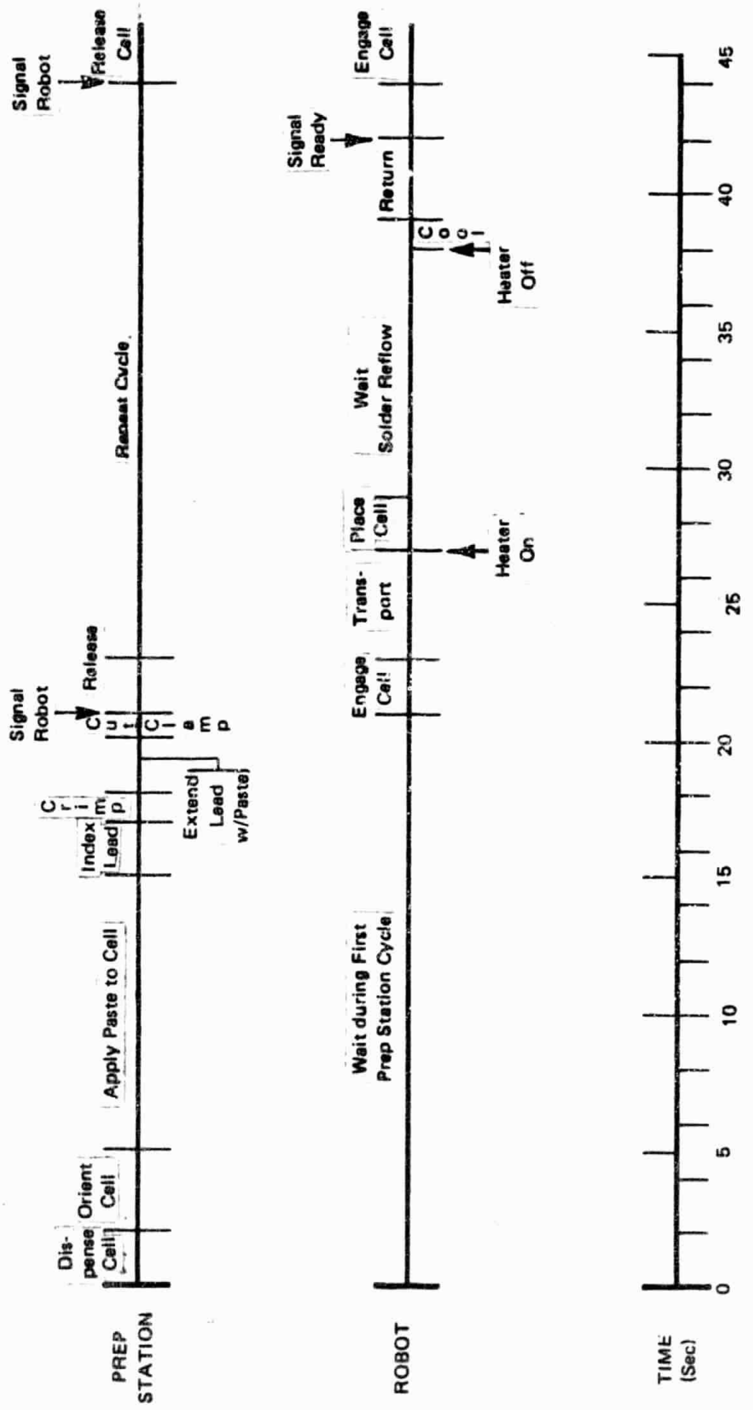


FIGURE 3-5
PREVIOUS CELL PREPARATION AND PLACEMENT CYCLE



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can be seen, a certain amount of dead time exists for each mechanism on the preparation station. This dead time was minimized by overlapping operations.

The first step in modifying the controlling program was to perform a detailed timing study of the entire cell preparation cycle. This allowed us to determine which steps could be done concurrently (e.g. the ribbon could be feeding while the cell is settling) and which must be done sequentially (e.g. the cell must be oriented before solder paste is applied). Using the results of this study, the program was modified overlapping several operations. The preparation cycle time from start of cycle to robot pickup command is now 8.5 seconds compared to more than 14 seconds previously (a 40% reduction). Figure 3-6 shows the new preparation cycle in which each mechanism on the station has been given its own line to show the overlapping. This again points out the advantage of programmable digital control. We were able to effect this reduction in cycle time with no change in the hardware (except for the solder paste dispensers as described previously and below) by simply reprogramming the actions into a more efficient sequence.

It should also be noted that this 40% reduction in cycle time was achieved <u>without</u> the use of simultaneous motor operations. Computer control of stepper motors is a non-trivial task requiring the computer to make thousands of calculations per second. Keeping track of more than one motor at a time would require a significant increase in the controlling program's complexity. Even if simultaneous motor operations were used it would decrease the cycle time by only about one second. We felt that the point of diminishing returns had been reached since this small gain would not be worth the large investment in manpower to expand the program. In addition, this would do nothing to reduce the cycle time of the two longest functions: cell settle and orient.

Two of the operations that were overlapped are ribbon feed and cell solder dispensing. To accommodate this, the front end of the solder dispensing manifold tapers down to a sharp leading edge, forming a ramp where it meets the ribbon at the edge of the vacuum chuck. After the dispenser is in position over the cell, the ribbon is fed up this ramp and over the top

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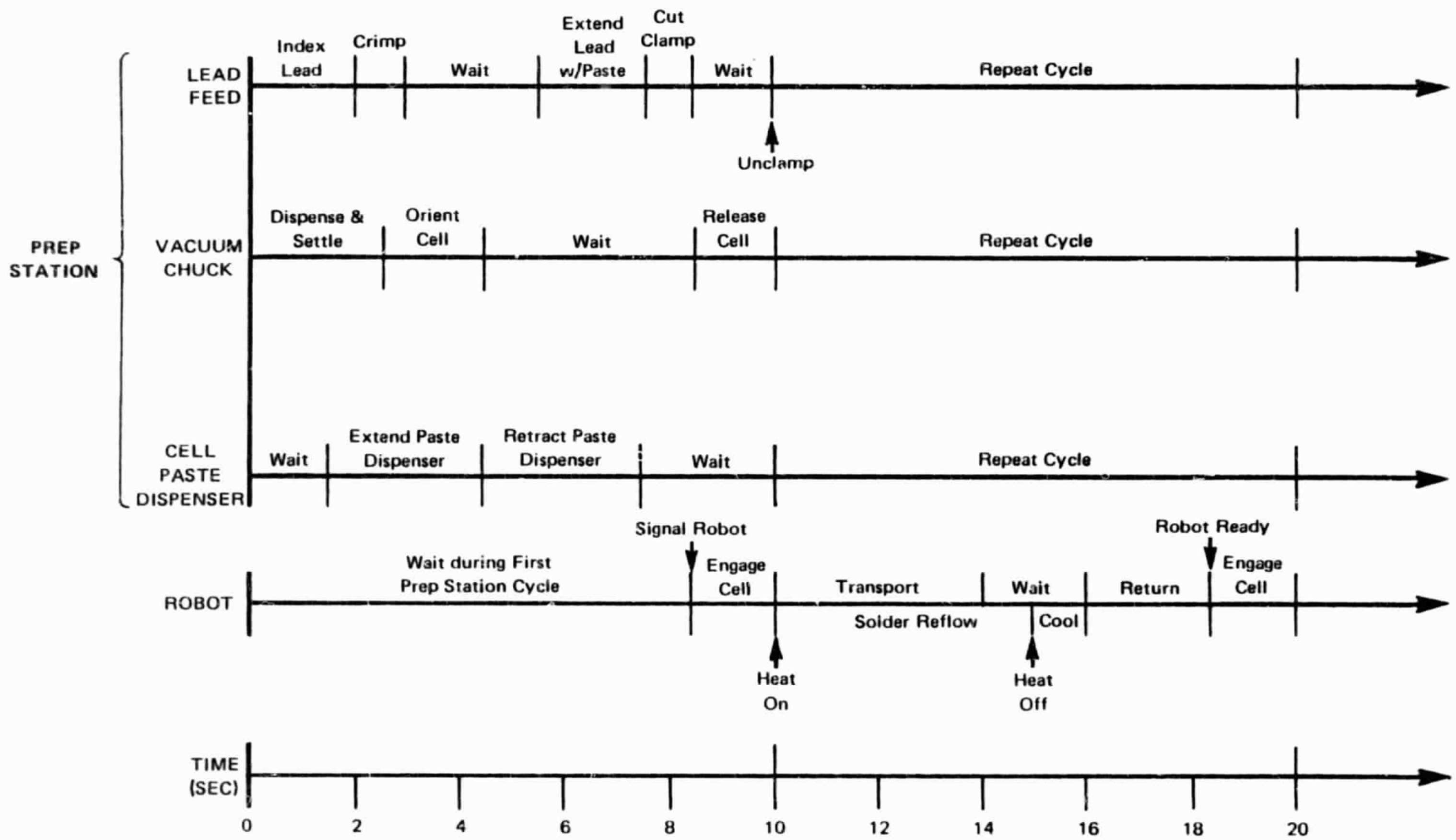


FIGURE 3-6
NEW CELL PREPARATION AND PLACEMENT CYCLE

of the dispenser. There is a groove cut into the ramp and top of the dispenser to act as a guide. When the dispenser retracts, the lead simply lays down on top of the cell. In addition to reducing cycle time and improving in ribbon positioning accuracy, this technique eliminates the problem of the lead "plowing" into the solder paste during ribbon feed.

The big unknown in reducing cycle time involved the robot. In our first full size program, the robot laid up a 35 cell (1'x4') string in 345 seconds for an average of 9.86 sec/cell. This was only pick-and-place (P&P) time and did not include a heating wait which adds approximately 3 sec/cell.

Unfortunately, even subsequent optimizations of the robot's program could not bring the P&P time below 320 seconds per string (9.14 sec/cell), far short of the 245 seconds required to make the 10 sec/cell rate with the heating wait included. The reason for this is that the Unimate 2000 is a very large machine for this application and takes a long time to "zero out" its position at each step when working at maximum accuracy. Since, as mentioned in Section 3.1, we are working at the extreme limit of the 2000's accuracy, the overall cycle time suffers.

Unimation has recently introduced a line of small robots specifically designed for electronic and other small parts assembly. This line, called the PUMA series, is all-electric (as compared with the 2000's hydraulics) and is programmed via a sophisticated computer language rather than the somewhat primitive teach-and-repeat method. The PUMA's small size and low mass make it more than twice as fast as the 2000 in P&P (albeit with a much smaller reach) and has an accuracy of ± 0.004" (0.1mm).

### 3.4 General Phase One Improvements

Although it does nothing to improve the accuracy or reduce cycle time, there is one more improvement that should be mentioned. This is the purchase and installation of a custom enclosure to house the entire cell preparation system. This enclosure (Figure 3-7, built by Crystal Mark in Glendale, California) performs far more than just a cosmetic function,

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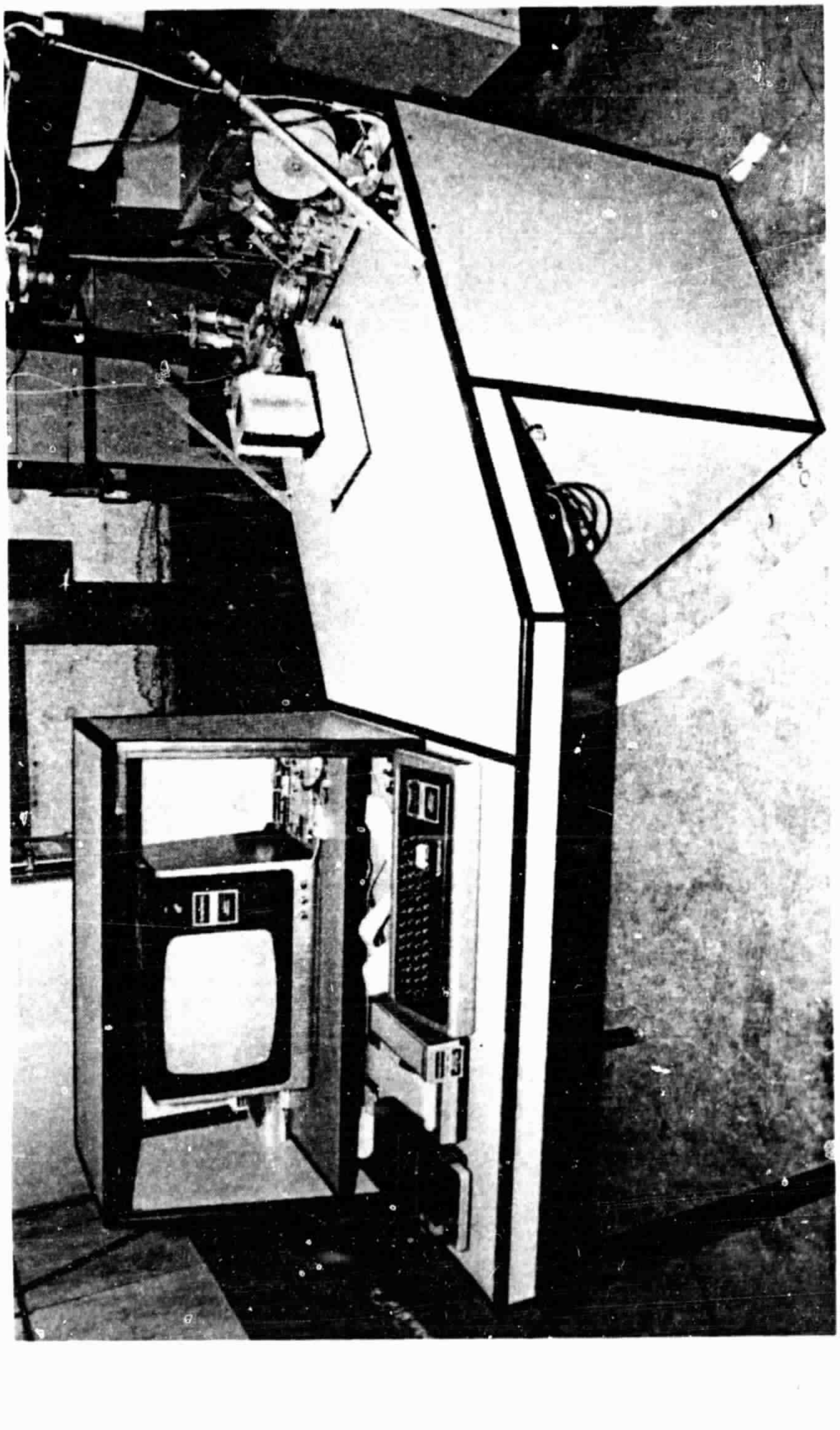

FIGURE 3-7
CELL PREPARATION STATION IN NEW ENCLOSURE

however. It consolidates the system into a single unit while protecting the electrical and mechanical components from contamination. The enclosure is actually two units joined on a $30^{\circ}$ angle.

The operator's section is a standard-height desk on top of which is a lockable console. Within the console is a shelf for the computer's video monitor and storage of manuals. The shelf has been placed 4" above the desk top to put the video monitor at the operator's eye level. The space beneath the shelf is used for storage of the other computer components (keyboard/processor, tape unit and printer). During use these components slide forward onto the operator's desk area. Under the desk's surface is an enclosed cableway 3" deep that runs under the entire desk area and over to the equipment area.

The top of the equipment section is a continuation of the desk level surface. Flush mounted onto it is the cell preparation station itself (Figure 3-8). Below the surface is an equipment shelf which is infinitely adjustable for height. The actual height is determined by the Siltec cassette unloader which sits on the shelf with its upper half protruding through the desk top. The height of the shelf must be adjusted such that the output belts of the Siltec line up correctly with the vacuum chuck in the preparation station. Beneath the shelf is an open equipment mounting area in which all of the pneumatic plumbing and valving as well as the computer interface electronics are located. There is also ample room to accommodate the additional electronics necessary for the Automated Lamination Station (described in 5.0). In this way, all of the interface electronics can be located in close proximity to the computer, which aids in reducing random signals that could produce errors. Additionally, all of the sensitive, low voltage information cables run in protected cableways to further reduce outside interference.

### 3.4.1 Installation Philosophy

The enclosure that houses the cell preparation station is the operational center of our entire system since it also houses the controlling computer and interface electronics. For this reason we

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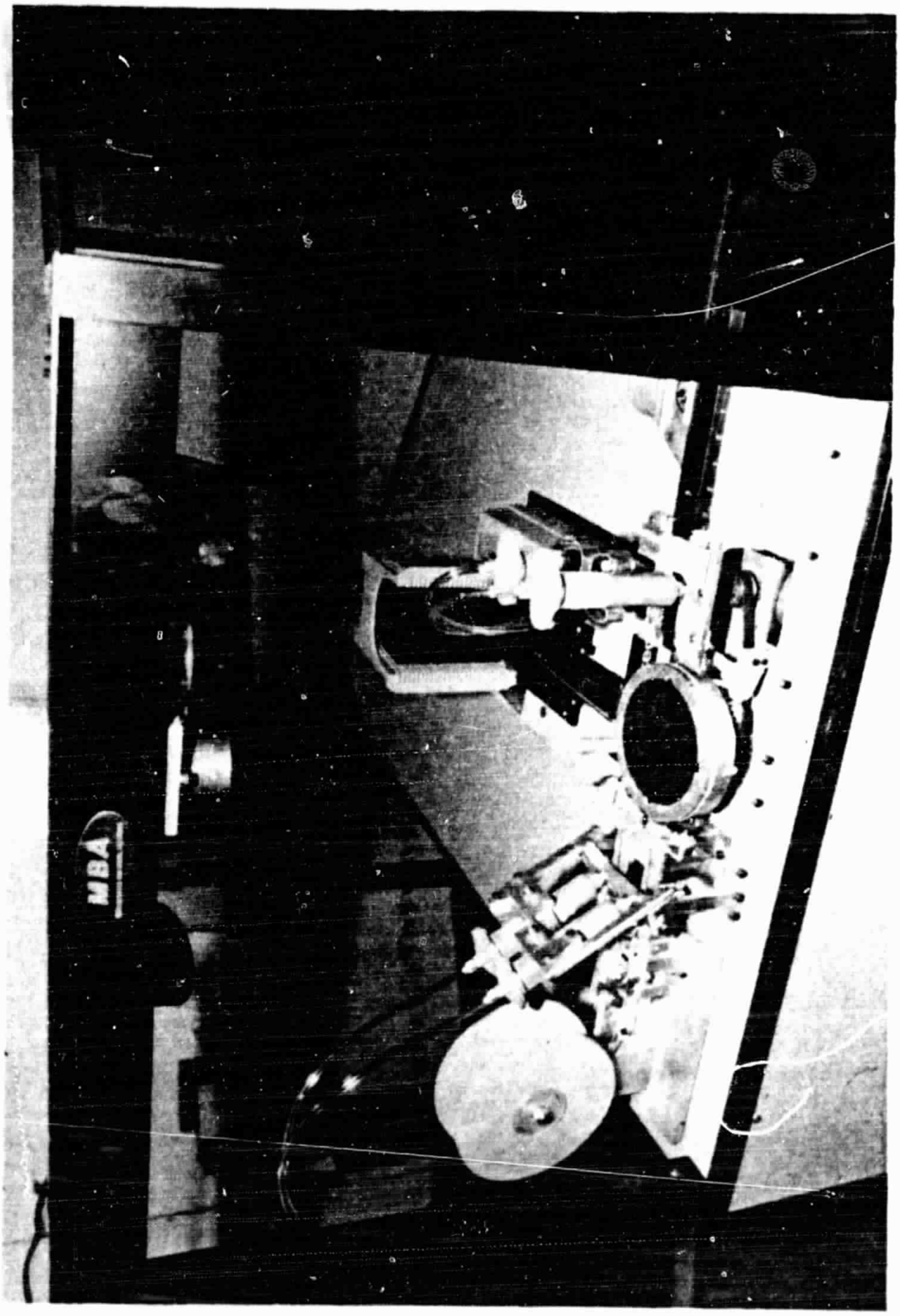


FIGURE 3-8
EQUIPMENT SECTION OF NEW ENCLOSURE

proceeded cautiously with the installation of the electro/pneumo/mechanical elements of the cell preparation station as well as the computer and associated electronics. Care had to be exercised in the placement of components and the routing of cables and tubing not only to conform to standard practices (such as separating power lines from information cables to avoid interference) but to allow for the orderly expansion of the system. This was required when the control and information functions of the Lamination Station, vacuum chamber and Edge Seal Station were integrated.

After the enclosure arrived, but before any actual wiring began, we had to decide on an installation philosophy. All wires, cables and tubing had to be routed in a neat and professional manner (of course) yet still conform to the restrictions mentioned above. All electronic, electromechanical and straight mechanical support equipment had to be mounted permanently but still allow for the necessary expansion without having to rearrange and remount equipment.

On the other hand, it was recognized that this is a prototype machine and that considerable troubleshooting and/or modifications would be necessary. This requires that the machine be easy and flexible to work on. For this reason, none of the electrical cables or pneumatic tubing in the equipment section that must pass through a surface (cabinet wall, desk top, etc.) use hard connections. All of these are accomplished through the use of quick disconnect connectors. This affords easy access to any part of the machine as any panel can be removed without disconnecting any cables and/or tubes. In addition, all of the connections to the preparation station itself contain extended service loops. These allow the entire desk top containing the preparation station to be removed (gaining direct access to the support equipment beaneath it) and still have the station be operational.

### 3.4.2 Installation - Operator's Section

The major decision here was to mount the main computer interface board on the console wall (next to the video monitor, Figure 3-9), rather than in the equipment section as originally planned. This reduces the interconnect cable length from over 3 ft. to about 1 ft. This should

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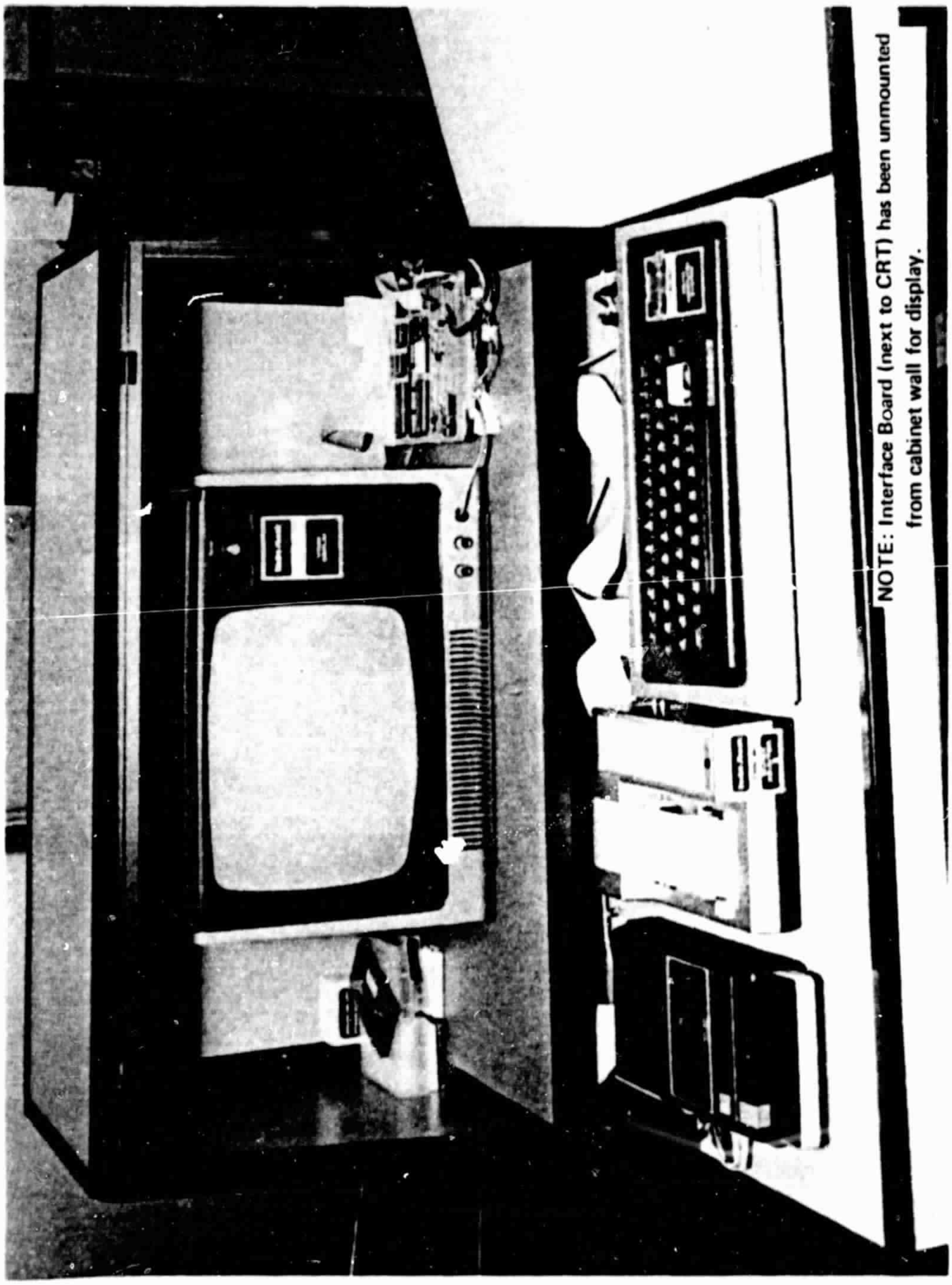


FIGURE 3-9
OPERATOR'S SECTION

eliminate any possibility of outside interference.

### 3.4.3 Installation - Equipment Section

The Siltec cassette unloader, as mentioned above, sits in the center of the equipment shelf (Figure 3-10). To one side of it on the shelf are the two power supplies. One of these is regulated and powers all of the computer interface and other information handling electronics (such as the op-amps and A to D converter). The other is unregulated and powers the electro-mechanical devices, i.e., the solenoid valves and stepper motors. These two supplies have enough capacity to satisfy all additional requirements of the Automated Lamination Station, the Automated Edge Seal Station and Automated Vacuum Chamber with the exception of the chamber heater. While this heater (described in Section 5.3) consumes approximately 2.6 kw, it operates off of standard line voltage (115 VAC) so no power supply is needed.

On the other side of the Siltec are the seven solenoid valves. Due to a lack of space in the previous enclosure these were mounted upside down under the shelf. This arrangement made access difficult for both initial wiring and plumbing of the valves and later inspection and modification. The new arrangement makes things much easier to work on.

Underneath the shelf (Figure 3-11) is a general equipment area that contains both electronics and pneumatics. The electronics consist of the high-current driver board and the optical interface board. The pneumatics include the eductor (which generates a vacuum for both the chuck and solder paste dispensers) and the main inlet manifold. Also located in this area, on one of the cabinet walls, are the input air connector and valve and the various information/power connectors for cables going to the robot, the Lamination Station and Edge Seal Station.

In addition is the second driver board which operates the stepper motors, solenoid valves and control functions of the equipment in the two remote stations. The solenoid valves themselves are not mounted in the enclosure, however, as this would mean long runs of pneumatic tubing and a loss of efficiency.

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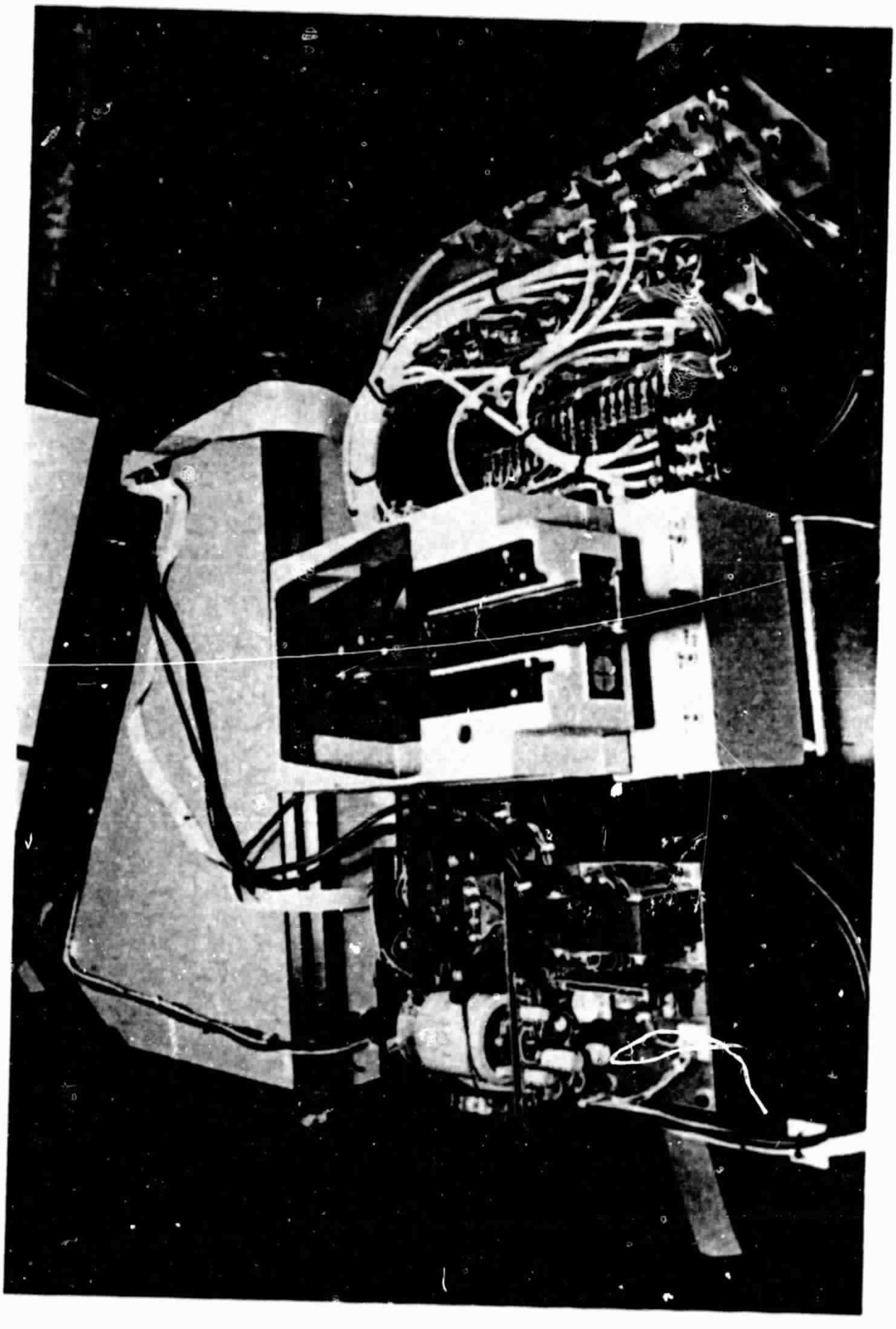

FIGURE 3-10
EQUIPMENT SECTION, TOP OF SHELF
(Desk Surface Removed)

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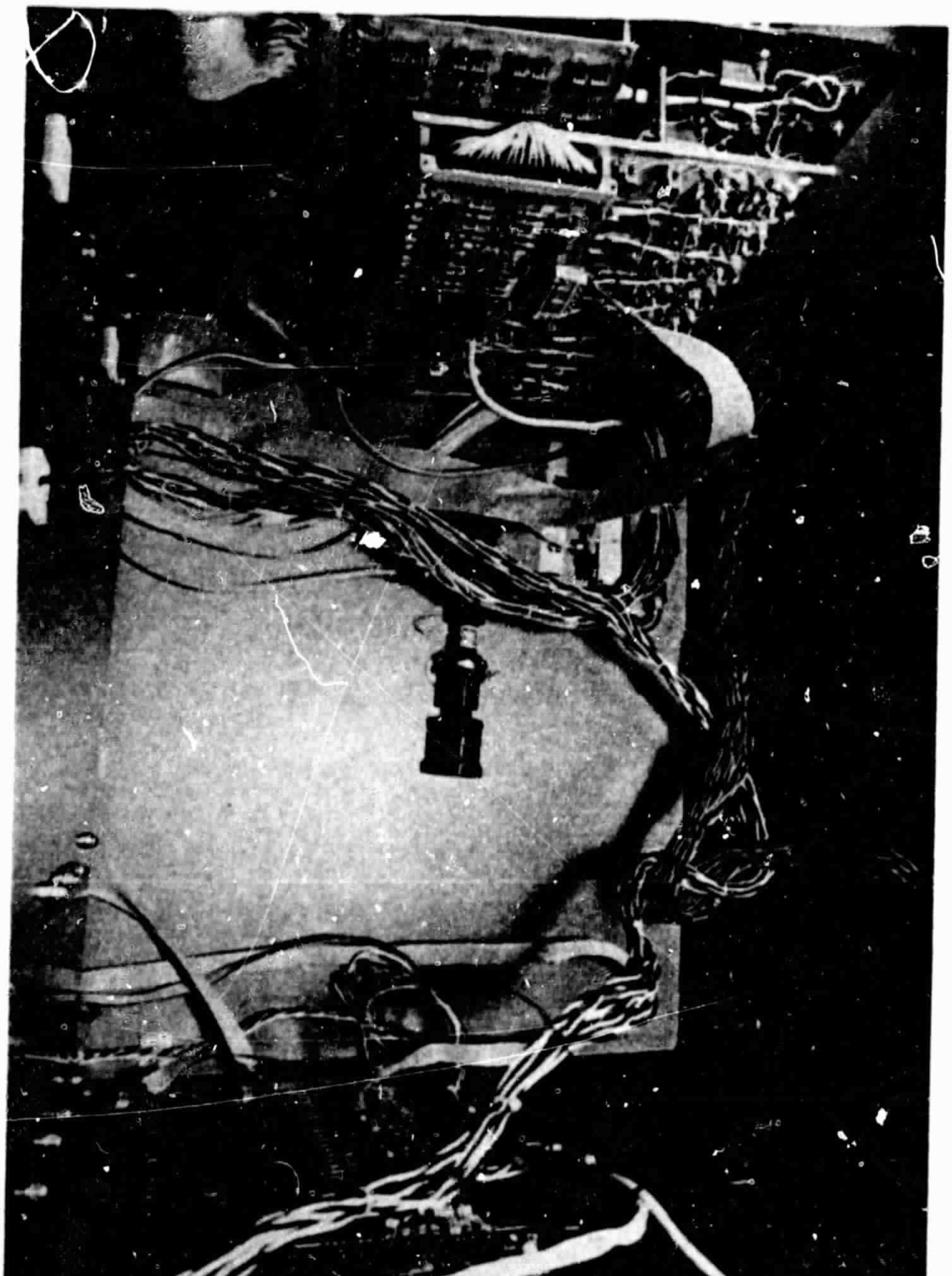

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FIGURE 3-11
EQUIPMENT SECTION, UNDER SHELF

## 4.0 PHASE TWO: EXPAND CAPABILITY OF EXISTING SYSTEM

This phase of the project involves adding capabilities to the existing cell stringing system to make it more adaptable to a real life production situation. This involves the detection of both broken cells, or cells with bad metalization patterns, during preparation; and poor bonds after soldering.

Implicit in both of these is correction, i.e., once the problem has been detected, action will be taken to correct it. Since the robot is our only cell handling device, it was assumed that it would be the one to remove or repair the bad cell. As we investigated deeper into the problem, however, we came up against a serious obstacle.

In order to take corrective action, the robot must be able to do conditional branching, that is, the robot would have to deviate from its pick-place-and-solder routine to a pick-and-dispose or resolder-and-retest or unsolder-and-dispose routine on command from the controlling computer. Although conditional branching is a trivial task for all general purpose computers (it is, in fact, the basis for all machine intelligence) it is beyond the capability of the Unimate 2000. While it would be possible to modify the robot to do conditional branching, it would be a very major modification (in essence a "brain transplant") and is beyond the scope of this contract.

In light of the above, it was decided to modify the contract to downrate the activity in this section from actual hardware modifications to that of a study. The aim of the study would be to investigate various methods of achieving the stated goals without using the robot. The results of this study follow.

### 4.1 Broken Cell Detection and Disposal

Detecting a broken cell, or one with a substandard metalization pattern, is a fairly straightforward expansion of the cell orientation routine.

The normal cell preparation cycle starts with the cell being ejected from the Siltec unloader. It glides off the belts onto

the vacuum chuck (turntable) which is where all of the preparation takes place. The surface of the chuck has a matrix of holes through which air is exhausted making the chuck into an air table. It is tilted approximately $5^{\circ}$ from the horizontal with four locating pins on the "downhill" edge. Once the cell has glided off the belts and settled against the pins, the airflow is reversed clamping the cell to the chuck. The chuck then rotates $360^{\circ}$ while an optical sensor aimed at the cell's edge measures the reflected light. The computer then plots (internally) the light level for each of the discrete cell positions (there are 800 steps per revolution or approximately $\frac{1}{2}^{\circ}$ per step). This plot is known as the cell's signature and its shape is very distinctive for a good, on-center cell. A simple pattern recognition program examines the signature's peaks and valleys to determine the location of the contact pads and the chuck is then rotated to the correct alignment. In order to detect broken cells, we would need only teach the program to recognize a few more signatures. The signature of a broken cell would contain a high flat plateau representating the place where the piece of the cell is missing and the sensor is looking directly at the shiny aluminum surface. An off-center metalization pattern (or a cell not centered on the chuck) would produce a signature with skewed peaks and valleys. A substandard or missing metalization pattern would produce low peaks or none at all.

Once a cell has been determined to be bad, its disposal (other than using the robot) is actually quite simple. Since the chuck is already at an angle, we need only rotate the chuck so that the locating pins are "uphill" and turn on the air. The cell will then glide off the chuck and fall into a disposal container.

## 4.2 Solder Bond Testing

This section of Phase Two was investigated with some preliminary testing hardware. A method of contacting the lead was developed (Figure 4-1) that allows contact with the cells when the robot is standing off 1/8". For actual electrical testing, two brush contacts would have to be used, of course.

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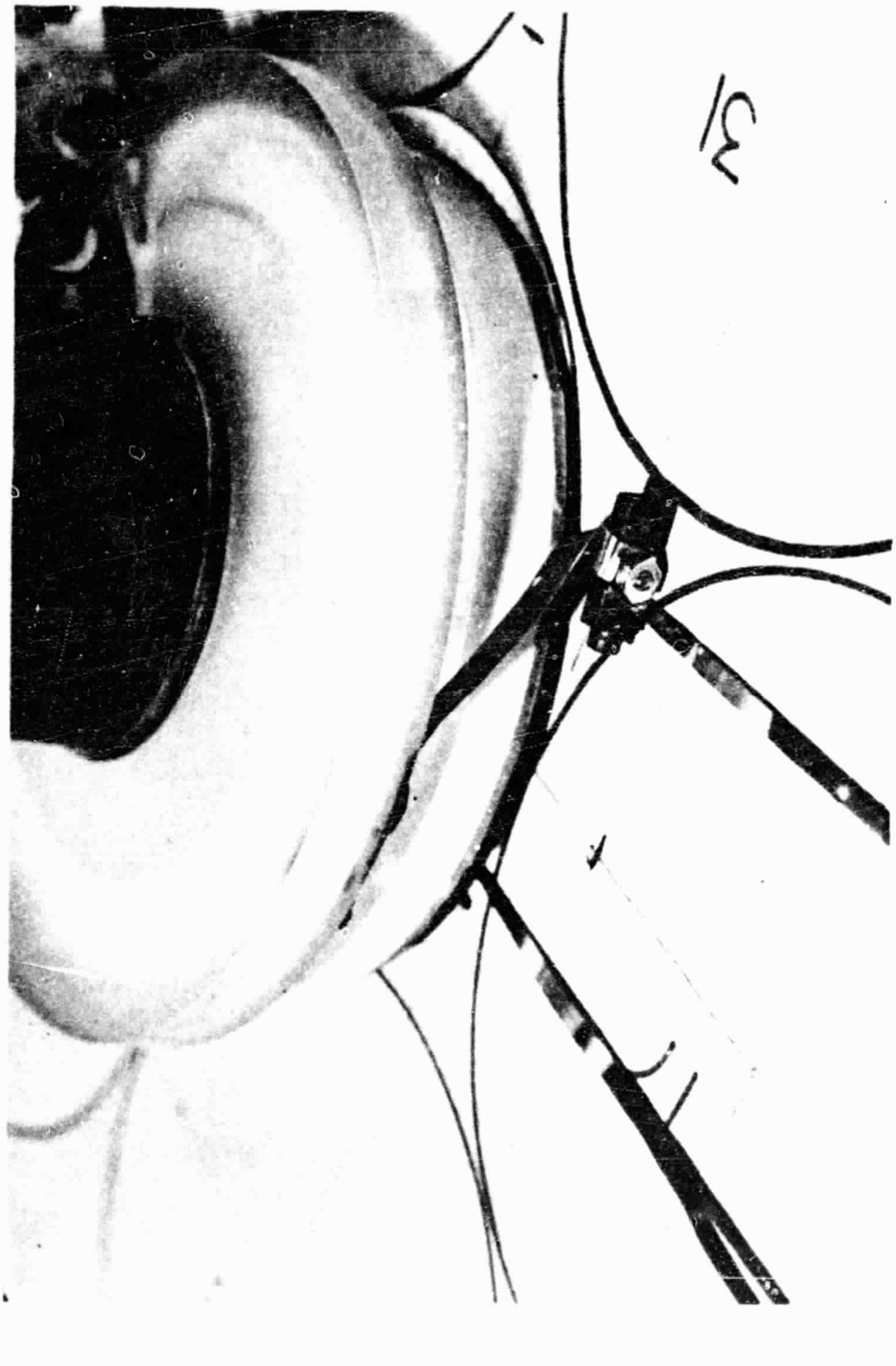

FIGURE 4-1
SPRING LOADED BRUSH CONTACT ON END EFFECTOR

The technique used is a simple resistance test. This test measures the resistance from one lead, through the solder joint, across the metalization pattern, through the other solder joint and out the other lead. (This test would work only for cells with parallel interconnect leads). A second set of contacts would be measuring the back solder bonds.

Early measurements were very encouraging. The resistance of a fully soldered lead was approximately 50 mΩ. The resistance through a lead with completely unmelted solder paste is approximately 500 mΩ. This order-of-magnitude difference seemed a good basis for a test until we investigated further. This revealed that 1) the resistance of a partially soldered lead falls logarithmically, or at least very non-linearly, between the two extremes mentioned (e.g. a lead soldered along only 10% of its length has a resistance of <100 mΩ) and 2) the brush-to-lead resistance alone is approximately 100 mΩ. This test, therefore, would only be reliable in detecting a totally unsoldered lead. Another form of testing would be required to determine a partially soldered condition. The standard IV output test is probably impractical since the cell is completely covered (i.e., in the dark) by the end effector.

There is another, unavoidable problem associated with post-solder testing. No matter what test scheme is adopted, the robot most wait until the solder joint has cooled before testing it. This eliminates the time advantage gained by our new soldering technique (Section 3.2.2).

Here too we have a method of avoiding the inflexible-robot-program problem, albeit not as elegantly as before. After each cell is tested (by whatever method is chosen) the results can be recorded on the computer's printer producing a "report card" on each module. If there are any problems, they would be noted and repaired off-line by a (human) repair specialist. This is exactly the technique used by automobile corporations who want to repair defects noted during assembly yet have to keep the assembly line moving.

## 5.0 PHASE THREE: AUTOMATED LAMINATION STATION

This is the largest part of the program as it deals with the development of the Automated Lamination Station. This station consists of three major components: 1) the vacuum platen end effector for the Unimate robot, 2) the Lamination Layup Station and 3) an Automated Lamination Chamber.

### 5.1 Vacuum Platen

In the design of the vacuum platen (Figure 5-1), it was first decided that it should be able to pick up sheets of cover glass and finished laminated modules, as well as circuits of interconnected but unlaminated cells. This is required since only one robot will be handling all three types of materials and it would be too cumbersome to change end effectors during this robot's routine.

The limiting factor in the design was the pickup of the 35 interconnected cells. Each cell must be individually supported because the interconnect leads cannot be relied upon to hold the cells in registration.

For actually picking up the cells, we used 35 discrete vacuum cups. To insure a good seal to the cell, we chose a vacuum cup which fits between the two leads on the cell surface. Additionally, they are a bellows type design which allows approximately 1/2" of compliance in the vertical direction and up to $60^{\circ}$ of angular misalignment when contacting the cells. Each vacuum cup is attached to its own small eductor which generates a low grade, high flow rate vacuum from compressed air supplied by a manifold. The 35 eductors are attached to the manifold which is in turn supported by a trusswork. Figure 5-2 is a close-up of the underside of the platen showing the eductors and bellows type vacuum cups. The trusswork is then bolted to the robot which supplies the air for operation through its internal plumbing normally used to operate a pneumatic clamp.

When testing the vacuum platen, only one significant problem

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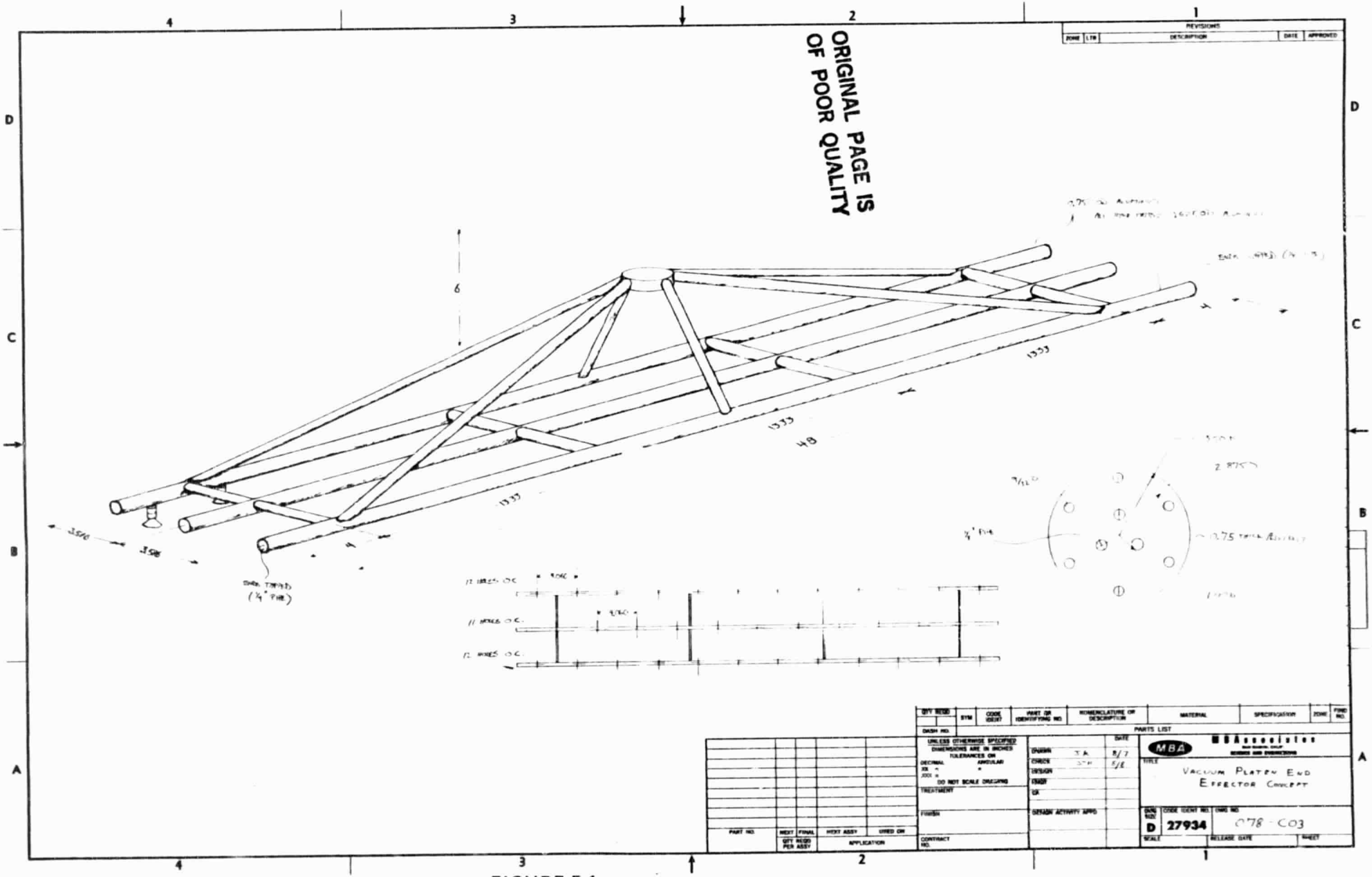


FIGURE 5-1
VACUUM PLATEN END EFFECTOR CONCEPT

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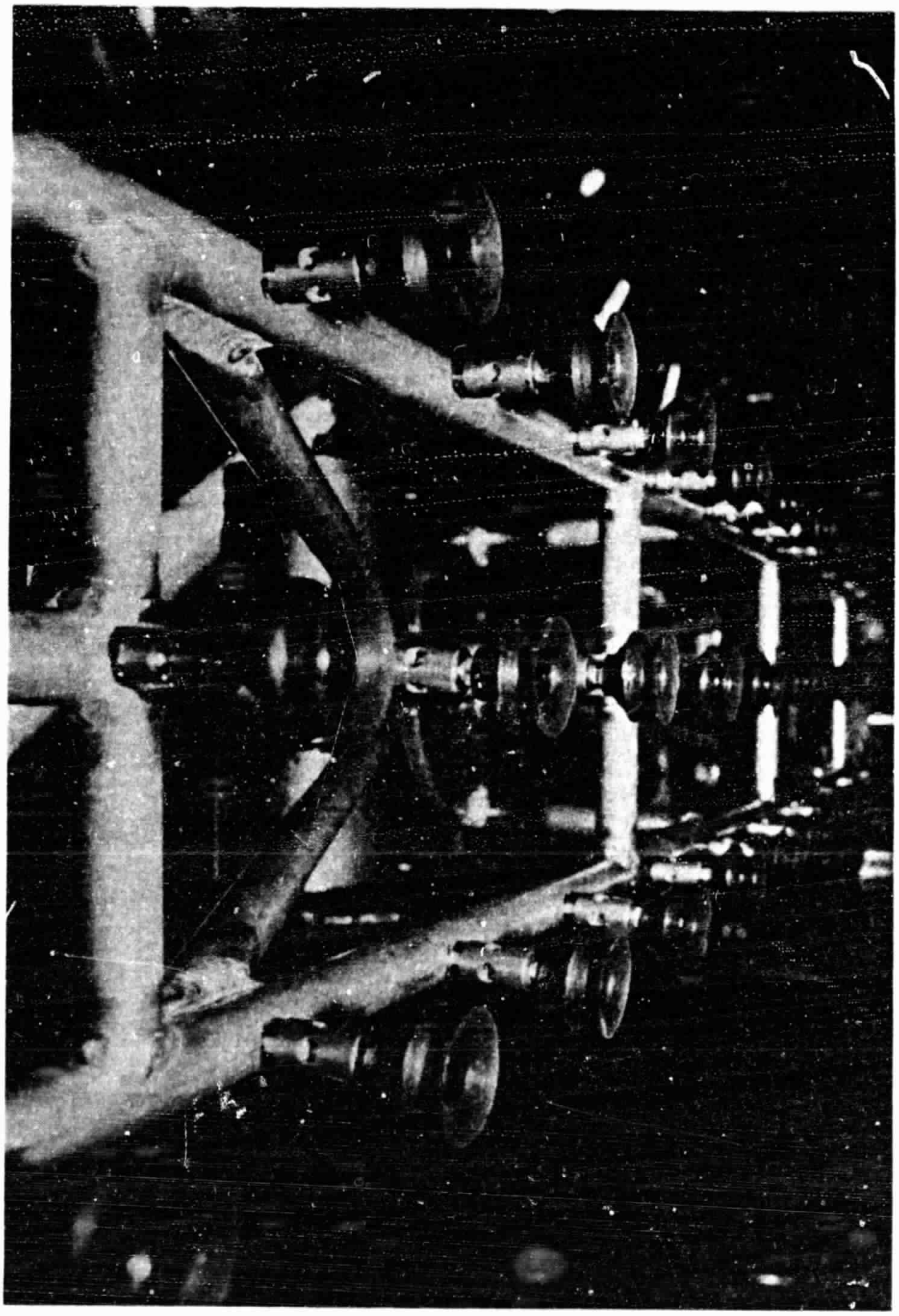

FIGURE 5-2
UNDERSIDE OF VACUUM PLATEN SHOWING EDUCTORS
AND BELLOWS VACUUM CUPS

was encountered. This was a large pressure drop in the air lines due to the high air flow rate through the vacuum platen (resulting from the large number of eductors used). It requires a minimum of a 20 psi drop across each eductor to insure a tight seal with the cells. However, the pneumatic plumbing required to enable the robot to lay-up and solder cells (with the other end effector) is far too restrictive to be used with the vacuum platen. The plumbing was, therefore, completely redone to allow the end effectors to be used interchangeably. A manual push-pull valve (operable from outside the robot) is used to switch between the highly controlled, restrictive plumbing needed for lay-up and soldering and the direct, high flow rate required by the vacuum platen.

The tests of the platen consisted of picking up 35 discrete cells as well as picking up the 8 lb finished laminate as shown in Figure 5-3. Even a 1'x4' piece of MBA Glass Reinforced Concrete (our panel substrate, see Section 6.0) weighted to simulate a finished panel (approximately 21 lbs) was handled without problems.

In its final configuration, the vacuum platen is able to hold these materials while the robot goes through some rather violent acrobatics, far more severe than would be encountered during normal handling.

## 5.2 Lamination Layup Station

The function of the Lamination Layup Station is to cut, from roll storage, the various laminate materials and place them into the lamination chamber. The laminate, specified by JPL for this contract (Figure 5-4) was developed by Spectrolab and consists of a bottom lamina sheet (made of polyester coated Al foil, Craneglas, white EVA and Craneglas), the circuit of 35 interconnected cells, a top lamina sheet (consisting of Craneglas and clear EVA), and a sheet of tempered cover glass. The modules are nominally 1'x4'.

To simplify the handling of the lamination materials, we specified that the materials forming the top and bottom lamina sheets be supplied already rolled together in multi-ply rolls 1 ft. wide. It is not

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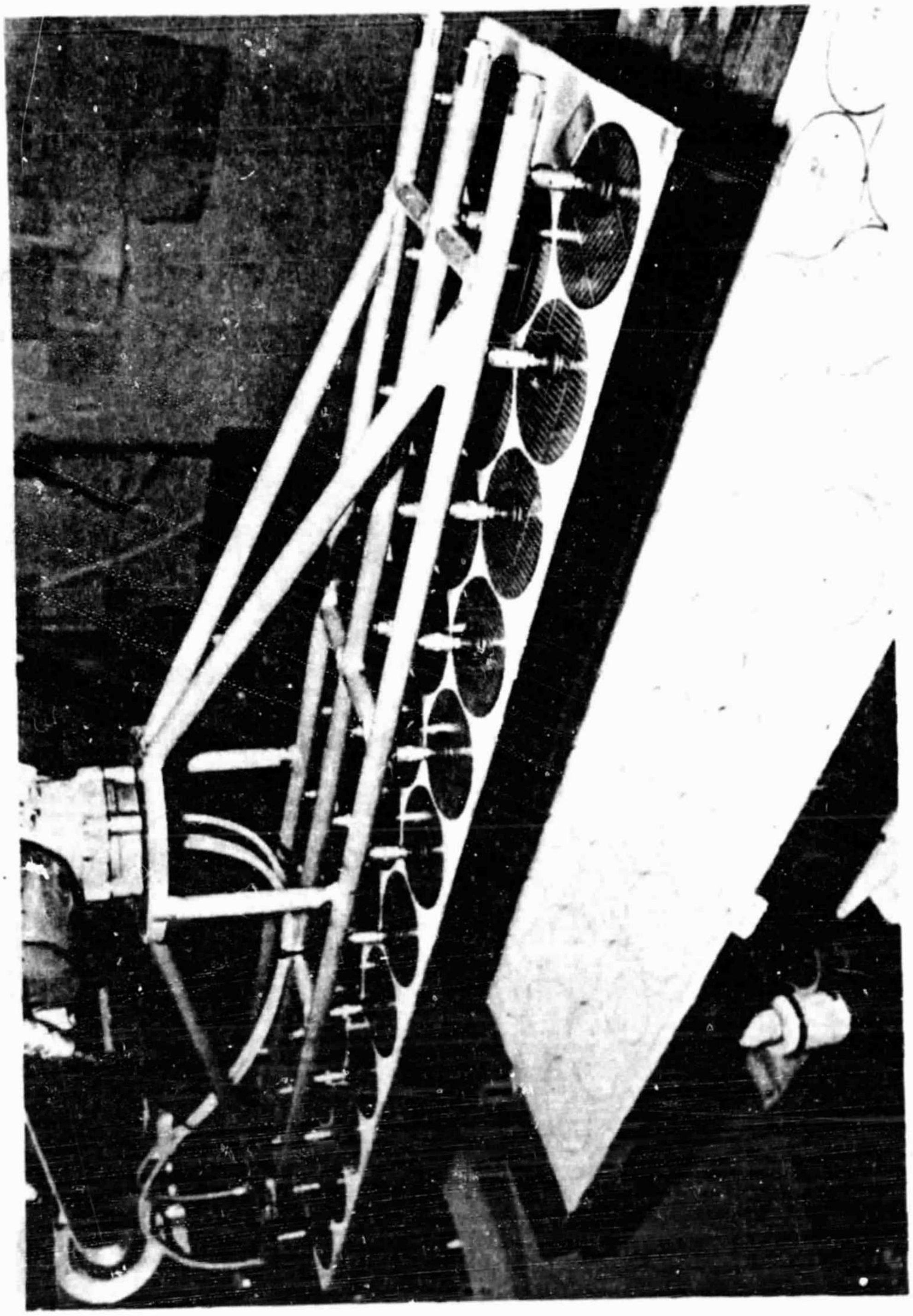

FIGURE 5-3
VACUUM PLATEN PICKING UP FINISHED MODULE

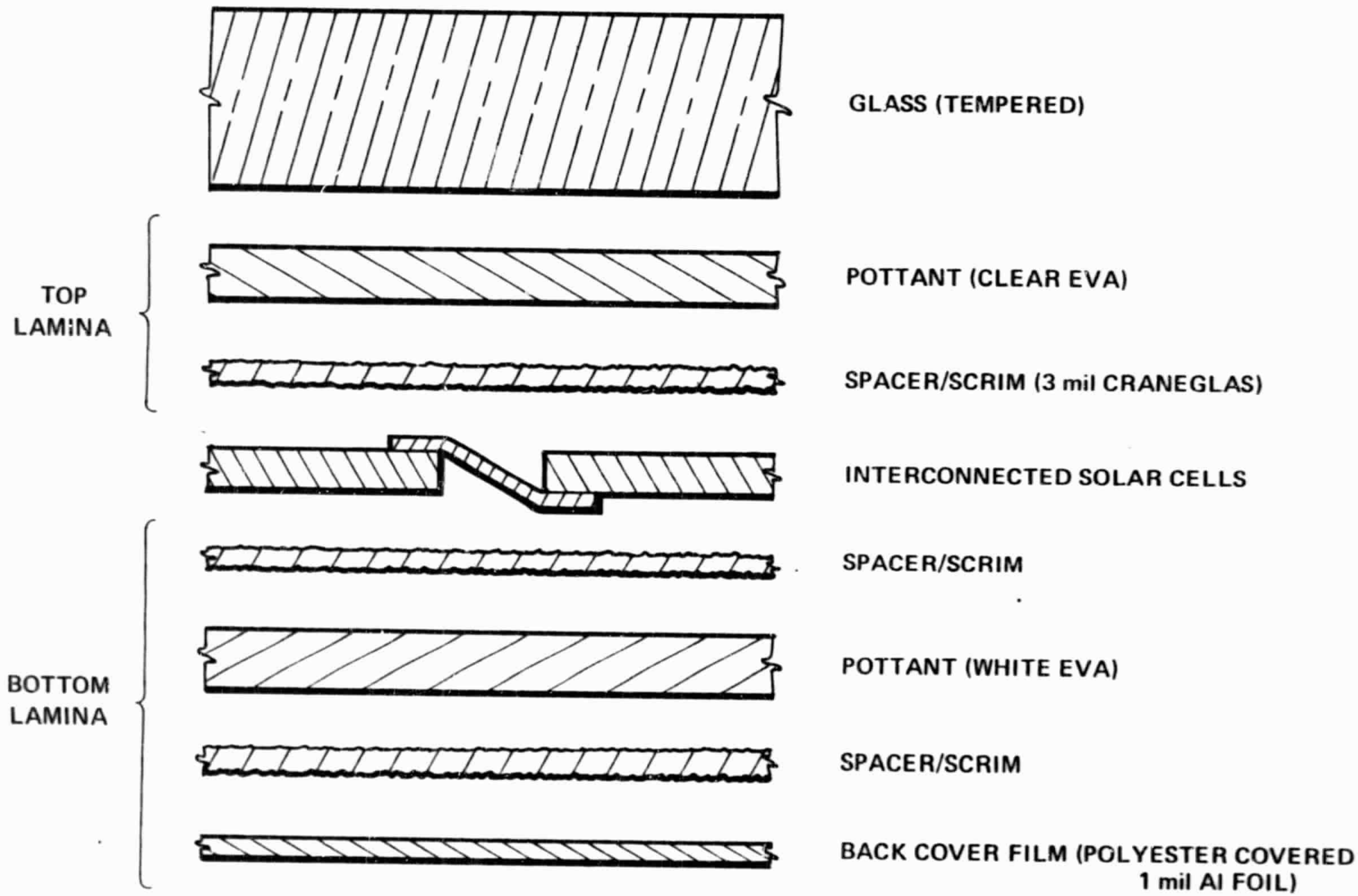


FIGURE 5-4
LAMINATE COMPOSITION



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uncommon for materials to be supplied in such a fashion and our investigation into the subject shows that this is how similar materials are handled in industry.

Because the cycle time of this station is limited by the pick and place time of the robot, we decided to have one station perform these tasks serially, rather than having many lamination chambers moving from station to station where only one task is performed by a station. This is the same design philosophy as used for the cell preparation station and we feel is best suited to this task also.

Figure 5-5 illustrates our conceptual design of the lamination station. At each end of the station is a feeding and shearing mechanism. One end handles the bottom lamina, and the other the top lamina. The lamination chamber lies in the middle. Running back and forth between the ends is a shuttle which clamps onto the edge of the materials and reels them out across the chamber.

The cycle for the Lamination Layup Station is as follows:

1) The bottom lamina sheet is fed via feed rollers through the shear into the shuttle which is parked at the end near the robot.

2) The shuttle clamps onto the end of the material.

3) The feed rollers separate.

4) The shuttle pulls the correct length of material (in our case 48") out through the shears.

5) The feed rollers re-engage to apply tension to the material.

6) The shear cuts the material off.

7) The shuttle pulls the material into its final position in the chamber.

8) The shuttle releases the material and parks at the far end.

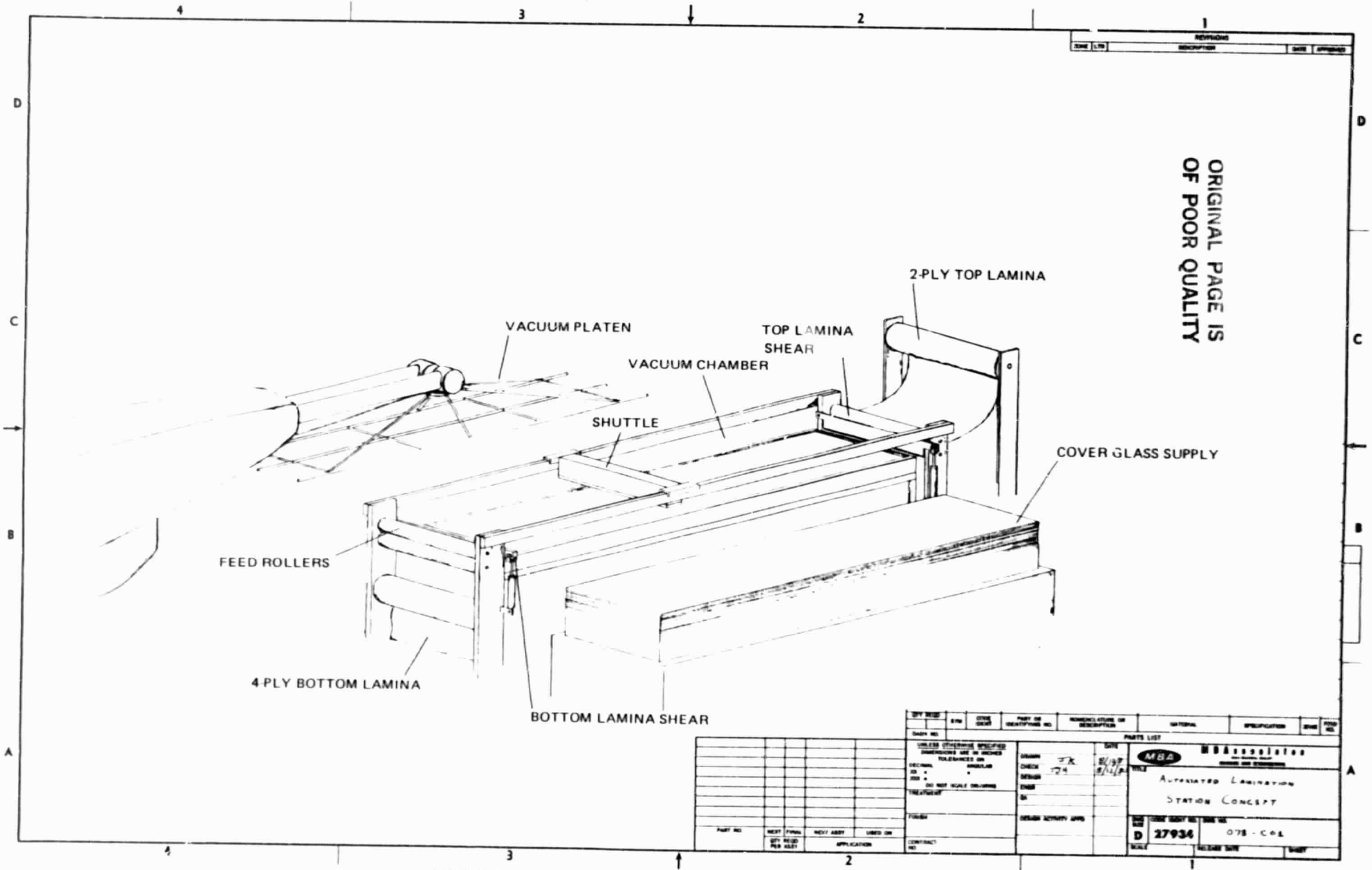


FIGURE 5-5
AUTOMATED LAMINATION STATION CONCEPT

9) The interconnected cells are placed into the chamber by the robot.

10) The top laminate is placed in the chamber in the same manner as the bottom laminate.

11) The robot places the cover glass into the chamber.

12) The chamber is ejected for vacuum/thermal cycling and a new chamber comes into place.

The final design closely follows this conceptual one with only a few minor variations. One of these is the position of the top lamina supply spool. In the original concept, the roll was placed above the feeding/cutting mechanism to allow the option of inserting the vacuum chamber from the end as well as the side. In the interest of expediency and the mechanical integrity of the frame, it was decided to restrict the design to side entrance only. This allows us to drop the supply roll down below the feeding/cutting mechanism (as with the bottom laminate) thus achieving a mechanical symmetry at both ends and further simplifying the design. The bottom laminate was originally placed low for clearance as this is the end that the robot approached from.

### 5.2.1 Mockup

To test this design, the shearing and placement of laminates in particular, we built a mockup station (Figure 5-6) with only one feeder-shearing mechanism and a shuttle. Although all the functions of the mockup were controlled manually, it was automated enough so that hands never actually touched the materials. The feed rollers were old conveyor rollers operated with a hand crank. The shear was a converted paper cutter operated by an air cylinder. The shuttle had closet door rollers running in tracks. The shuttle clamp was a flat plate which was activated by an air cylinder.

The mockup functioned amazingly well. There was no problem positioning the material in a simulated chamber or with cutting the materials.

The mockup was very useful in bringing to light many of the subtleties involved in this kind of operation and greatly aided the final

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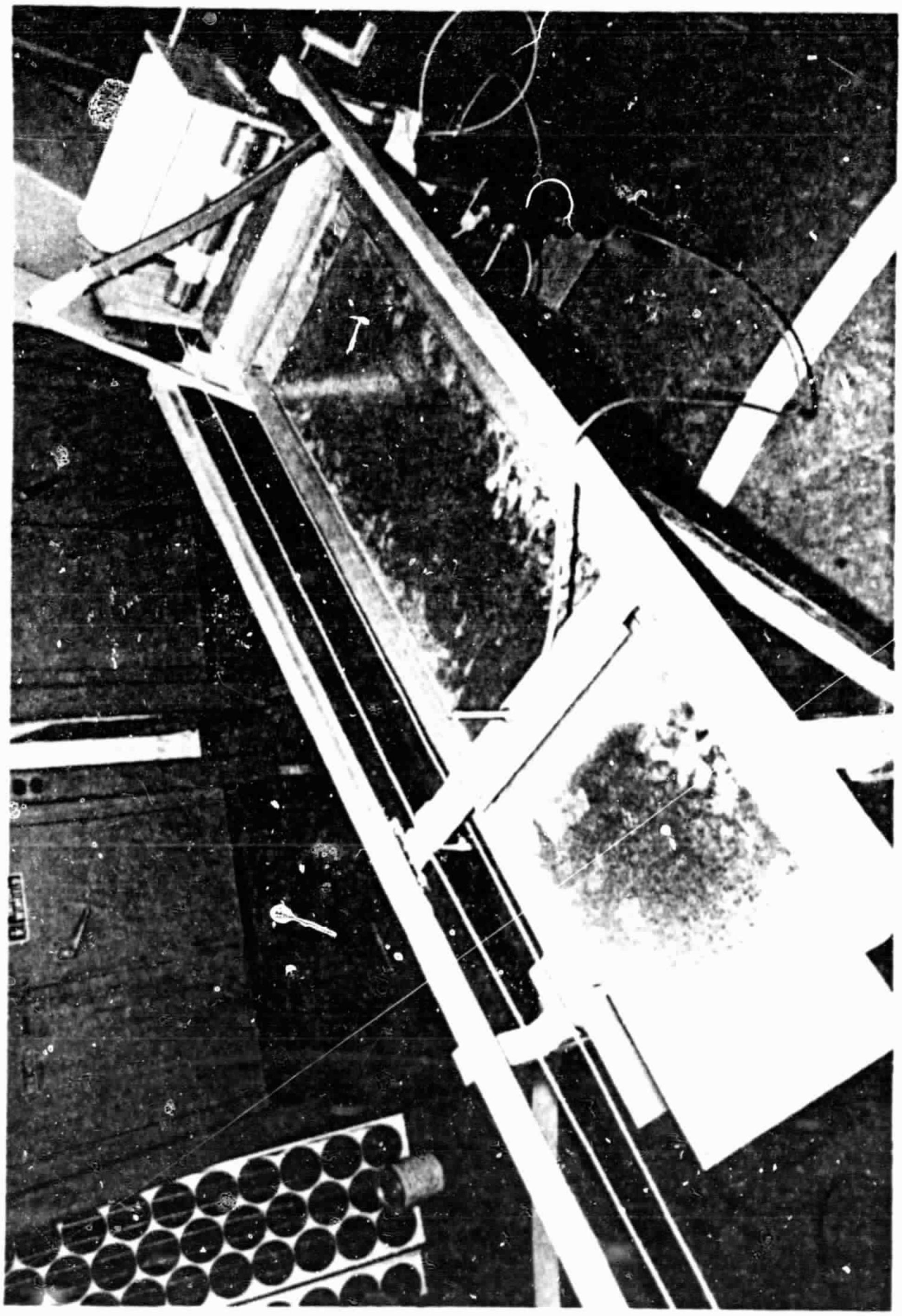

FIGURE 5-6
MOCKUP OF LAMINATION LAYUP STATION

design.

### 5.2.2 Design and Development

The final design proceeded quickly based on the lessons learned from the mockup. An artist's rendering (Figure 5-7) was produced from the actual layout drawings for JPL display purposes. It is included as a reference for the following discussion.

The intent of this contract was to use the JPL supplied Unimate 2000 robot in the lamination process. However, we have kept the design flexible enough that the robot-oriented steps in the process could be done by a simple transfer arm or even manually.

Figure 5-8 shows the Lamination Station in its final configuration. This, combined with the artist's rendering shows the location of all the components about to be discussed.

#### 5.2.2.1 Frame

The station's frame (Figure 5-9) is made from 3/16" wall rectangular and square section steel tubing with continuous fillet welds at all joints. This provides a very solid and dimensionally stable base on which to mount the various components described below.

#### 5.2.2.2 Shuttle

This moving clamp draws the encapsulant material from the feed rolls at either end and out over the chamber. It consists of a rectangular section body with a pneumatically operated clamp underneath. Flared surfaces guide the encapsulated material into the clamp. The shuttle is driven via a ball screw on one side only while the other side is allowed to float. Originally, this was on a set of needle bearing rollers placed above and below the frame rail which both supported the shuttle and offered torque reactions to the ball screw. However, it offered no resistance to rotation in the horizontal plane. In fact, a load of 30-40 lbs on the shuttle (well within the range expected for normal operation) would "cock" it severely enough to lock the ball nuts and stop the screw. To correct this situation and to give a more positive location of the

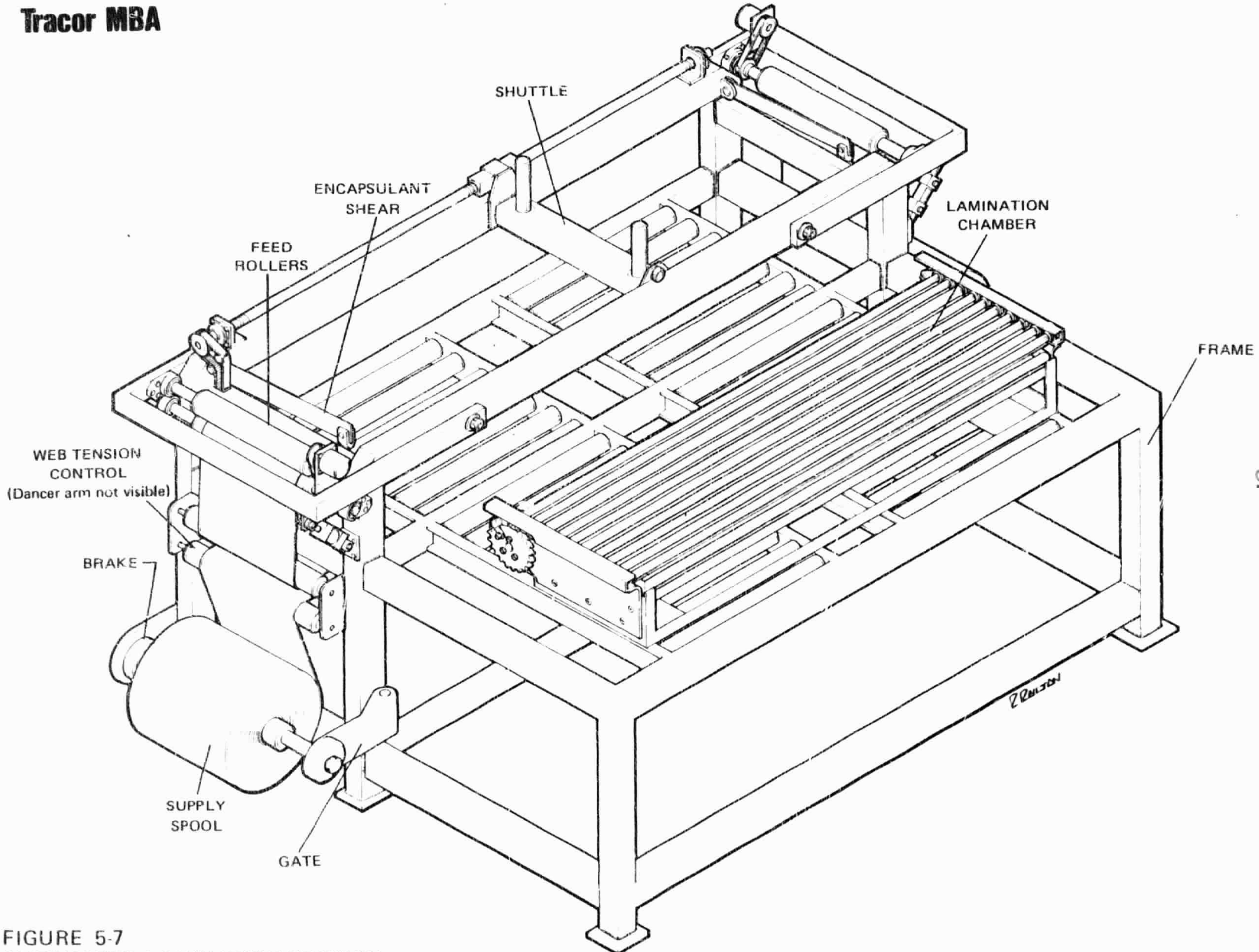


FIGURE 5-7
AUTOMATED LAMINATION STATION

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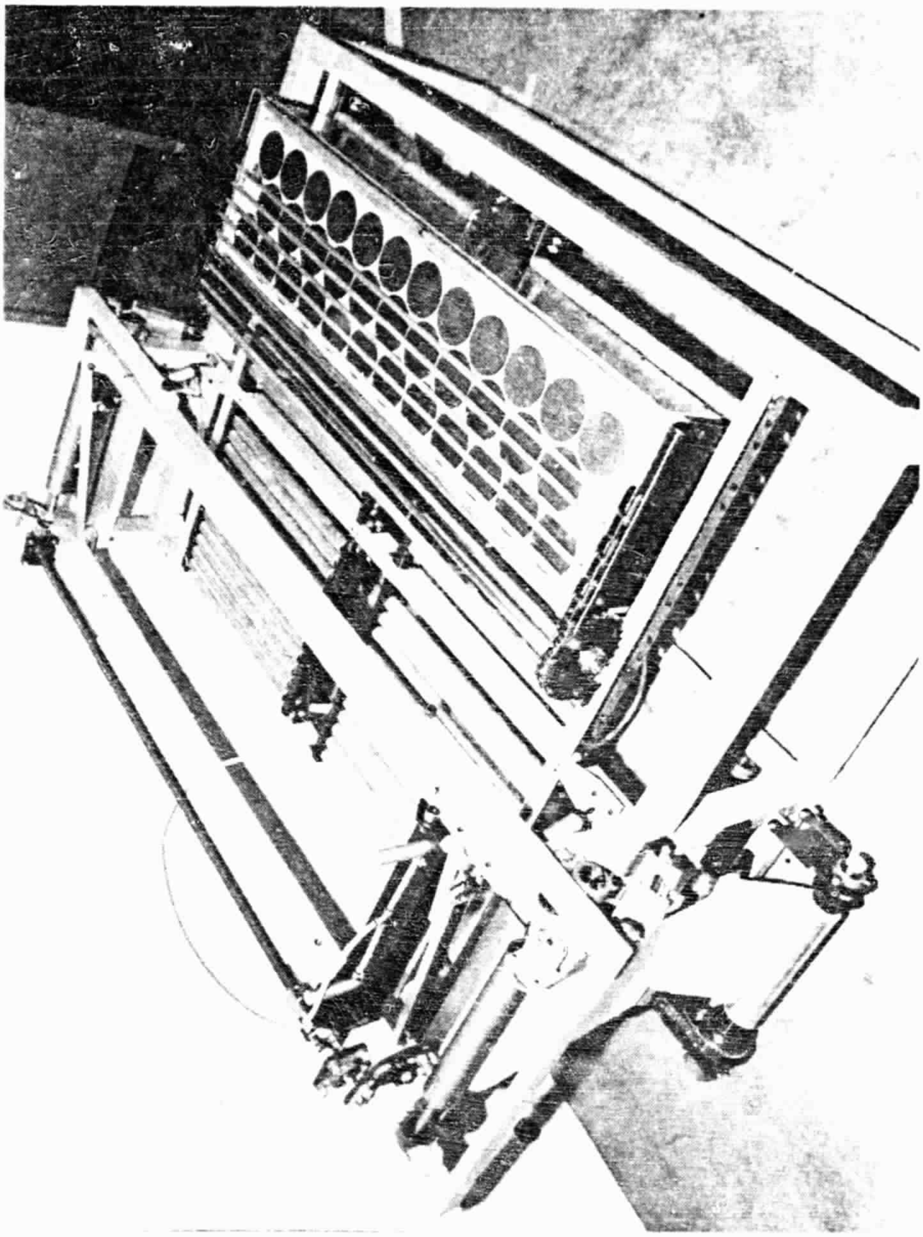

FIGURE 5-8
AUTOMATED LAMINATION STATION

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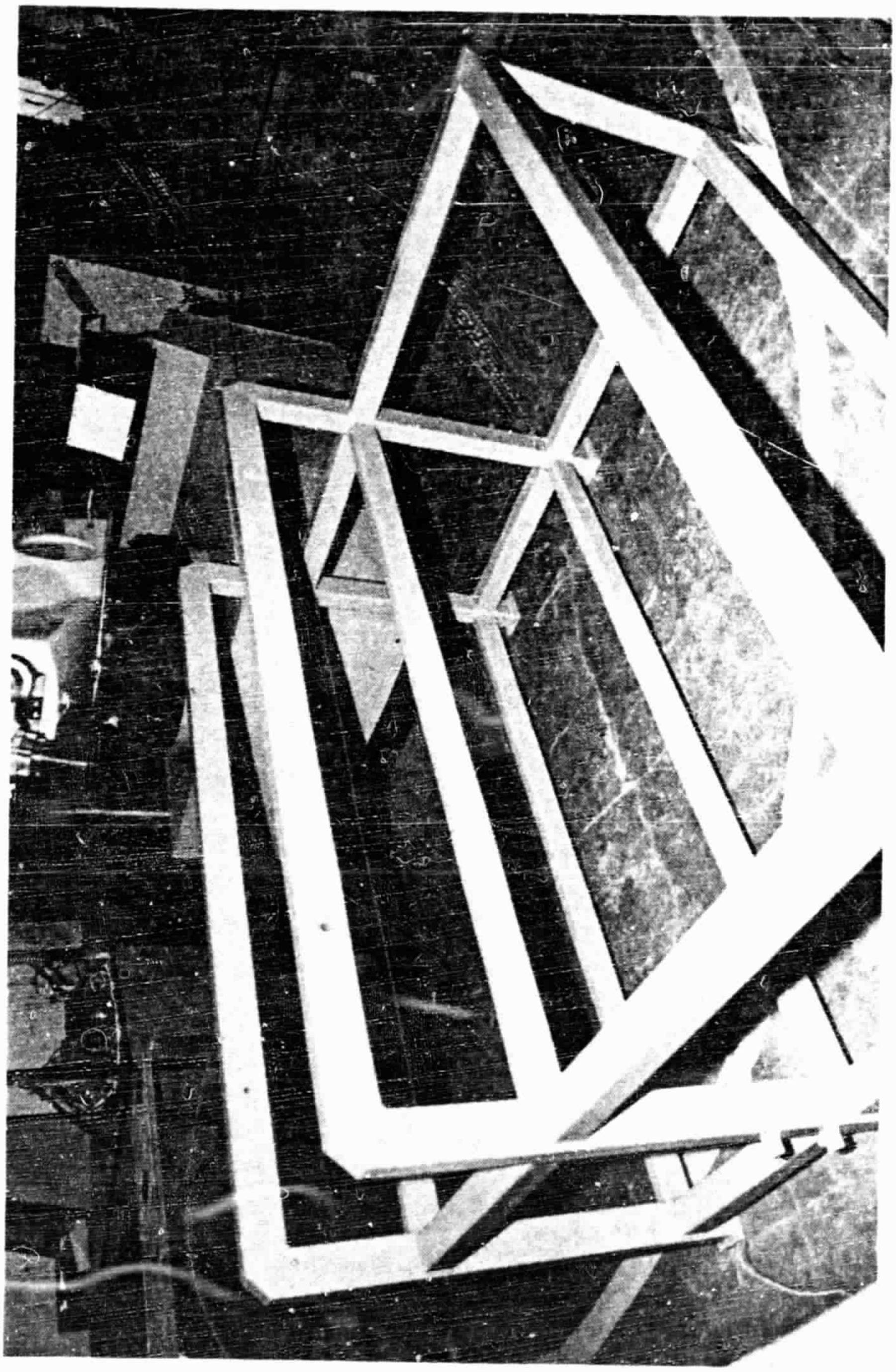

FIGURE 5-9
LAMINATION LAYUP STATION FRAMEWORK

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encapsulant, the top rollers on the free side were replaced with a floating wheel-and-rail set-up (Figure 5-10).

When the shuttle clamp was first connected to an air supply to check its operation, it did operate smoothly without binding but the action was somewhat sluggish. This was traced to solenoid valves which were too small. They were replaced with larger orifice valves which completely solved the problem.

The first operations of the shuttle drive motor showed that it, too, was undersized. Although adequate to move the empty shuttle or to pull the material with no applied tension, the motor would stall if even a slight tension was applied to the material. The motor has been replaced with a larger one with triple the torque. Its larger casing, however, has required that the motor be mounted in a location different than shown in the illustrations.

5.2.2.3 Feed Rollers

At either end of the machine are a set of pinch rollers whose job it is to feed encapsulant material from the supply roll into the shuttle. After the material is fed (about 6") the rollers must separate to allow the material to be pulled through them unobstructed. This is achieved by mounting the top roller (and also the drive motor) on a square U shaped pivot arm. The arm is raised and lowered by means of an air cylinder. We decided to fabricate the rollers in-house, rather than buying them off-the-shelf as with the conveyor and dancer rollers described below. This was done in order to maintain the extremely close tolerances necessary to assure that the rollers run true which will prevent the encapsulant from wandering as it is fed. After being installed and aligned, the rollers ran with only a 0.001" gap along their entire 18" length. The bearing mounts were drilled and pinned to maintain this alignment in the event of future disassembly.

In testing, the motors that drive the feed rollers were also found to have only marginally adequate torque. These were replaced with the next larger size (actually the old shuttle drive motor) to insure performance.

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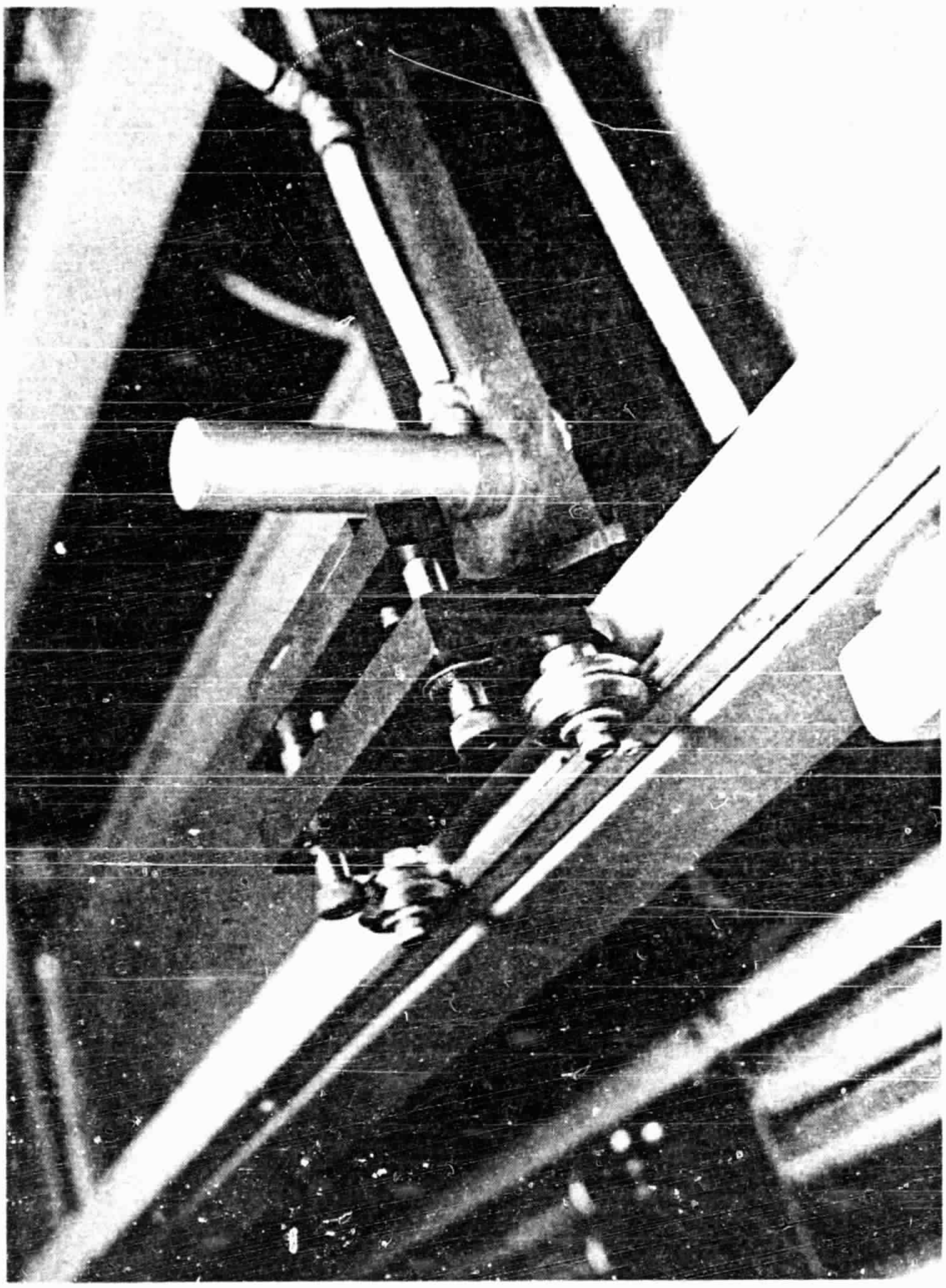

FIGURE 5-10
SHUTTLE WHEEL AND RAIL ASSEMBLY

In contrast, the valves and cylinders that operate the pivot arm were somewhat overdesigned. Right from the start they have been able to open and close the rollers with considerable authority.

5.2.2.4 Encapsulant Shears

To cut the encapsulant materials after they have been pulled by the shuttle, there is a shear located at both ends of the machine. Each of these consists of a fixed bottom knife bar and a moving upper knife bar (Figure 5-11). They are made of aluminum with the actual cutting surfaces made of hardened tool steel. The design is similar to the common office paper cutter although significant differences exist to adapt the concept to automated operation. If one were to look at a paper cutter, you would see that the moving blade is spring loaded to hold it tightly against the fixed blade. Also, both blades are beveled slightly (about $10^{\circ}$) from horizontal to insure a sharp point of contact. These features have been retained in our design. Looking again at the paper cutter, however, reveals that the blade is long and curved. This serves two functions. First, it allows the blade to contact along a moving point rather than all at once in a line. Second, it increases the stroke to allow the long stroke/low force human actuator to cut accurately. This had to be changed in our design as space restrictions dictated a short stroke (only a $10^{\circ}$ rotation of the moving blade). This is no problem as pneumatic cylinders can generate much more controlled force than a human arm in a short distance. The moving-point-of-contact is accomplished by careful attention to pivot points and linkage design.

There is one last aspect of shear design to be addressed. Once again, looking at a paper cutter, it can be seen that the moving blade, as seen from above, must move away from the fixed blade after passing through the cutting plane to further enhance the "point contact" of the blade. It also prevents the shorn material from binding before the cut is completed. This action can also be seen in a common pair of scissors. We are accomplishing this in the same manner as the paper cutter, with a cam or ramp that forces the pivot end of the moving blade away from the fixed blade progressively during the stroke. However, due to our short stroke, the ramp cannot be located right at the pivot as the ramp angle would

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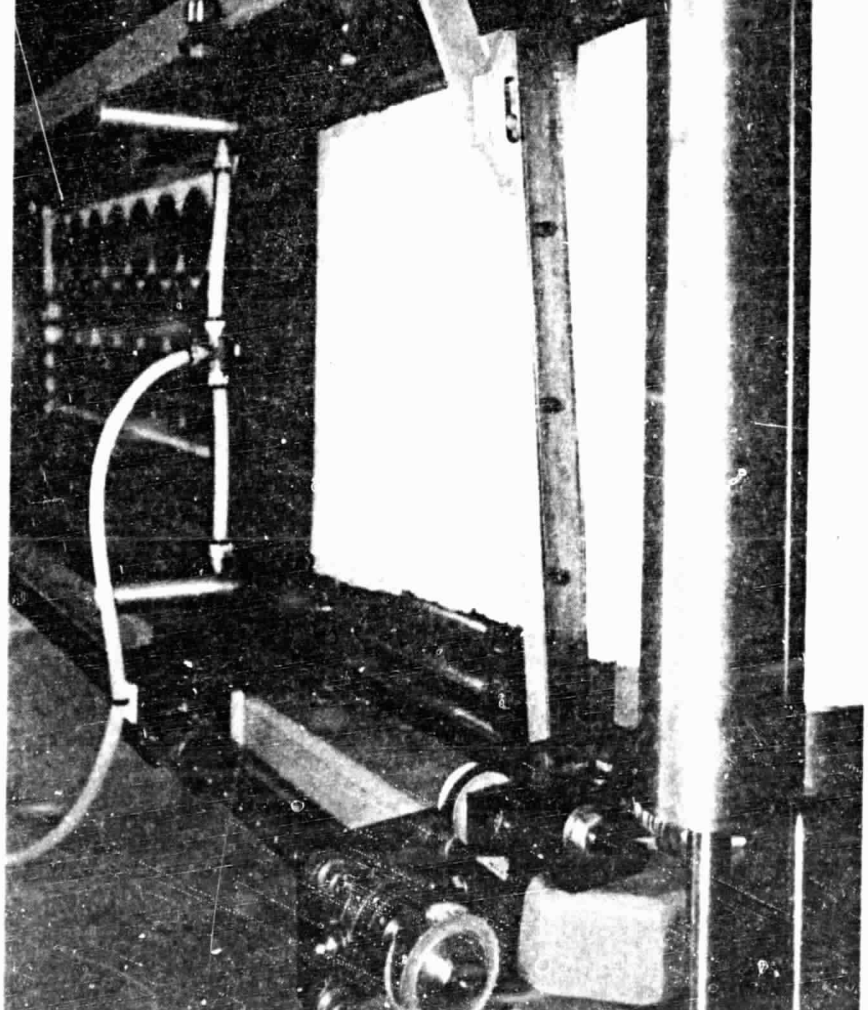

FIGURE 5-11
FEED ROLLERS AND SHEAR

Tracor MBA

be too severe. A short extension arm allows a more reasonable ramp angle. As you can see, the common paper cutter, despite its workaday function, is really quite a non-trivial device!

When first tested (after all of the linkages and brackets had been installed and adjusted) both shears cut the encapsulant materials beautifully when connected directly to shop air. However, when first connected through the solenoid valves, the shear's action (as with the shuttle clamp) was very sluggish and would not, in fact, cut the material. This was solved, again, by replacing the small valves with ones of larger capacity. In this case a pair of high flow rate, 5 port, 4 way spool valves were used, one for each shear. This type of valve allows the shears to be powered both ways (up as well as down) and exhausted both ways with only one valve.

The shears are truly frightening to watch when operating and, during development, were disconnected from their air supply most of the time as a safety precaution. OSHA style guards were fabricated and installed as a further safety measure.

5.2.2.5 Supply Spools

Both the top and bottom lamina supply spools are mounted on identical holding fixtures. The supply spool core is supported on either side by a self-centering mandrel on a common shaft. The mandrels will accept any core size from 2" to 3" ID. The shaft support on one side of the spool is fixed and the other hinged like a gate to allow the changing of spools. The fixed side has tapered roller bearings to support the weight of a full supply spool which will be cantilevered out from it during changing before the gate is closed. The hinged side has plain ball bearings. Also mounted on this shaft is the supply spool brake whose function is described in the next section.

Figure 5-12 shows the sequence for changing supply spools. First, (Figure 5-12A), the gate must be opened. This is easily done since the shaft is not one piece but rather unscrews like a pool cue at a point about one inch in from the gate bearing. Once the gate is open (Figure 5-12B) the setscrew on the mandrel is loosened and the mandrel slid off the shaft.

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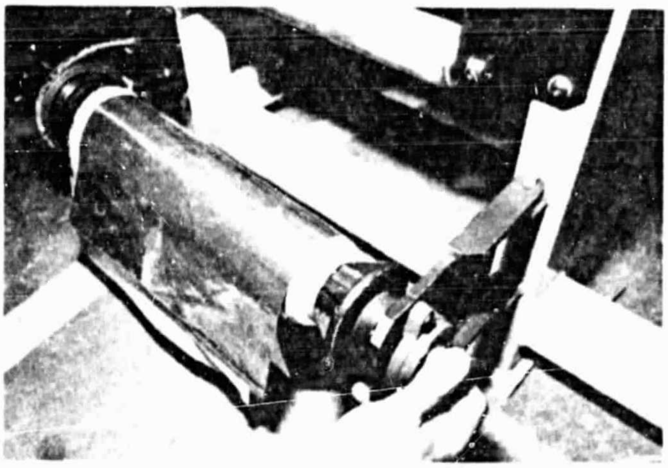
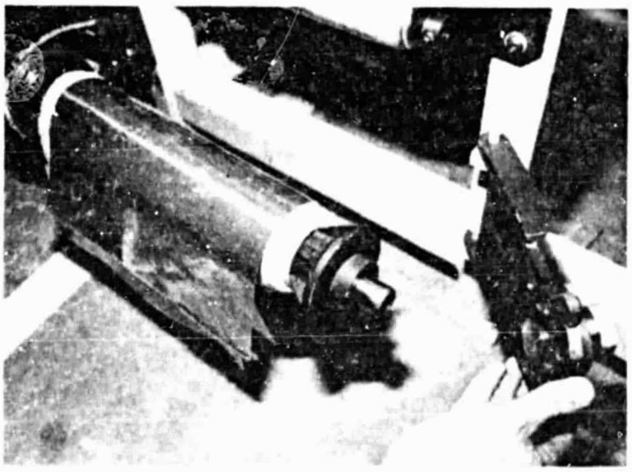


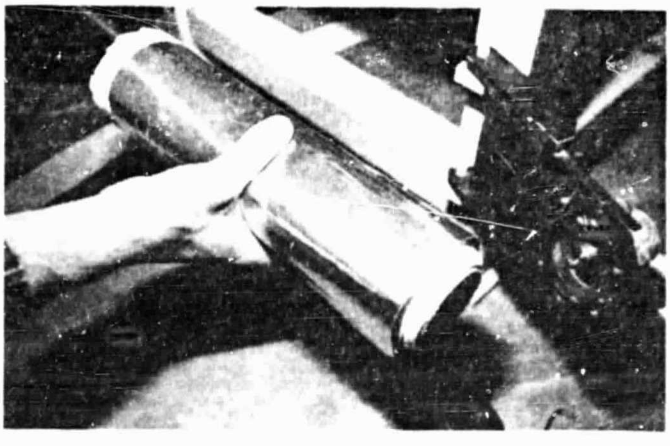
5-12A

UNSCREW GATE BEARING



5-12B

SWING GATE OPEN, UNLOCK MANDREL



5-12C

REMOVE MANDREL, SLIDE CORE OFF SHAFT

FIGURE 5-12
SUPPLY SPOOL CHANGING SEQUENCE

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Finally, (Figure 5-12C), the old core is removed. Loading a new spool is just the reverse procedure followed, of course, by threading the machine.

There is one aspect of the supply spools themselves that must be discussed. As stated previously, this machine requires that the supply spools be already cut to width (12" in our case) and rolled multi-ply (4 ply for the bottom lamina and 2 ply for the top). There are many machines available commercially that perform these tasks on an industrial scale but it is just not feasible for them to produce the comparatively tiny amounts that we require (a few hundred feet) to check out the operation of our machine.

To circumvent this problem, MBA has "jury-rigged" small versions of these large machines to produce the laboratory-scale quantities of material that we require.

The first of these machines (Figure 5-13) is called a Slitter-Rewinder. It is necessary because many manufacturers can produce materials only in standardized widths so, if they don't have an expensive commercial slitter, must sell it that way to customers. Clear EVA, for example, comes in 24 inch widths from Springborn Labs so the roll must be cut in half for our use. Due to its soft, plastic nature, the roll cannot be cut by bulk methods such as on a band saw. In addition, EVA contains a relase sheet (to keep it from sticking to itself) that must be slit simultaneously. Several cutting techniques were tried. Scoring (pinching between a sharp blade and a hard surface) worked well on the EVA but wouldn't cut the paper. Fixed razor blades were OK with the paper but clogged up and tore the EVA. The best solution we found was a high speed, toothless sawblade (actually an adapted pizza cutting wheel!). The inset of Figure 5-13 shows the blade poking through the clear EVA with the relase sheet beaneath it. Sawdust can be seen on the lower guide bar.

The white EVA presented still another problem. Since it is not yet a commercial item, our roll was a short, experimental run. This meant that it was rolled up by hand and the release sheet consisted of dozens of individual overlapping squares of tissue. The entire roll had

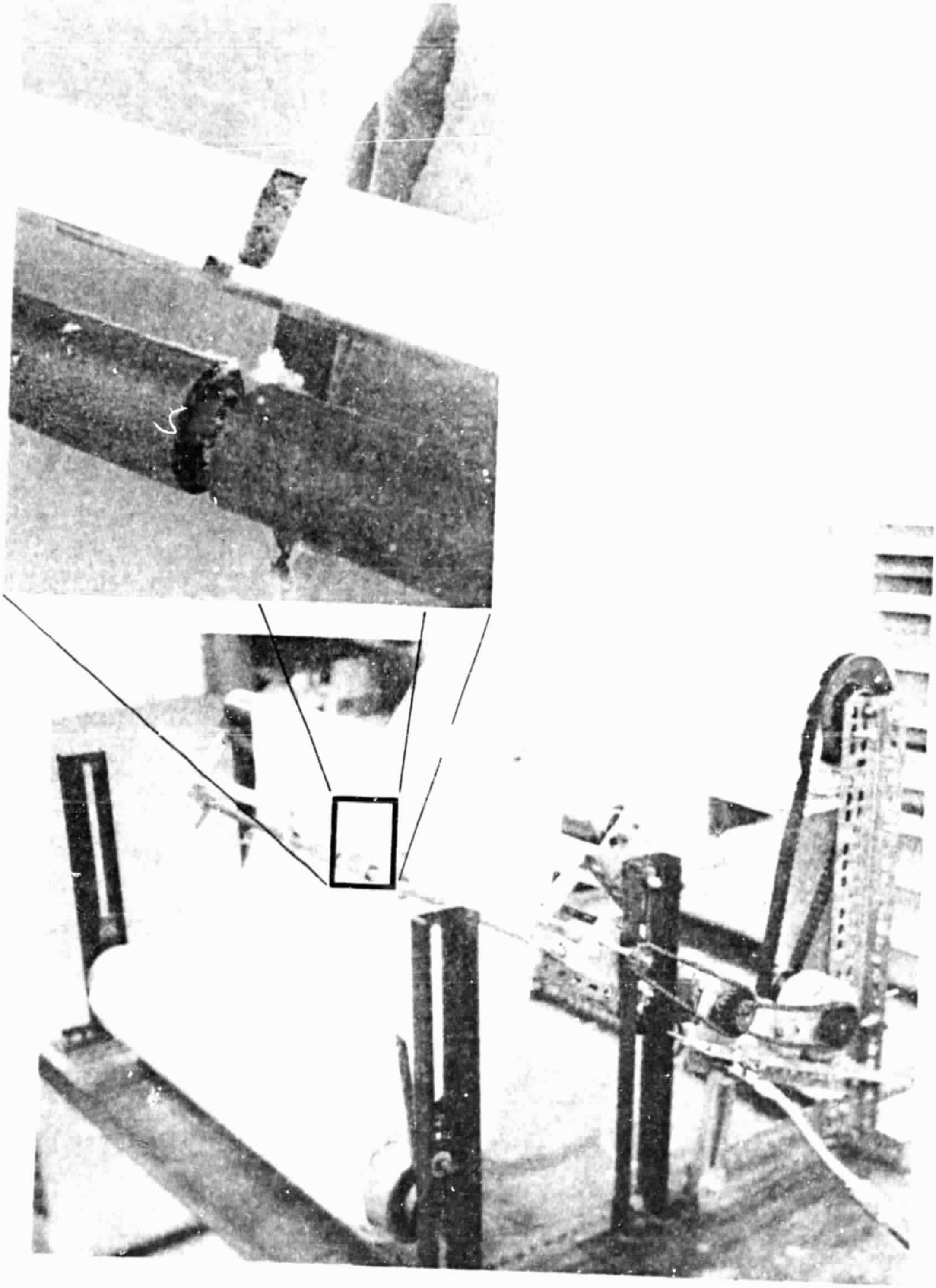

FIGURE 5-13
SLITTER-REWINDER

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to be first re-rolled replacing the individual sheets with a continuous one. Also, the roll was of an odd width (32.5") which we decided to slit into thirds. This meant two passes through the slitter (there is only one blade) resulting in a white EVA roll which is slightly undersize (about 10.8").

Once all the materials are the correct width, they must be rolled together in the correct combinations to form the supply spools. Figure 5-14 and 5-15 show the multi-ply roller we have devised. Figure 5-14 shows the machine set up to roll the 2-ply top lamina which consists of clear EVA and Craneglas. Note the release sheet falling from the EVA (the Craneglas, incidentally, acts as the release sheet in both supply spools). Figure 5-15 shows the same machine re-configured to produce the 4-ply bottom lamina which consists of Mylar coated aluminum foil, Craneglas, white EVA, and Craneglas. The inset shows how the four plys come together at the bottom (the edge registration plates on the side of the spool have been removed for clarity). After this picture was taken, a take-up spool was installed above the EVA roll to wind up the relase sheet as the EVA unwinds.

#### 5.2.2.6 Web Tension Control

In order to have good control over the lamination material (known as the web) it must be kept taut as it travels through the machine. The design tension was on the order of 3 lb. per inch of width (36 lb. total) for the bottom lamina and 1 lb./in. (12 lb. total) for the top. These values came from guidelines established by the thin film plastics and paper industry for their high speed machines (hundreds of feet per minute web speed). Whether they held true for our very low speed (15 ft./min.) machine had to be determined by experience. As expected, the necessary tensions were somewhat lower: approximately 1 lb./in. for the bottom lamina and less than 0.5 lb./in. for the top.

To maintain this tension in a controlled manner, the web passes over a dancer roller which is located between the supply spool and the feed rollers (Figure 5-16 , left). The dancer roller (so named because it appears to "dance" on the web during operation) is mounted on a vertical, pivoted arm (Figure 5-16, right) and performs several important functions

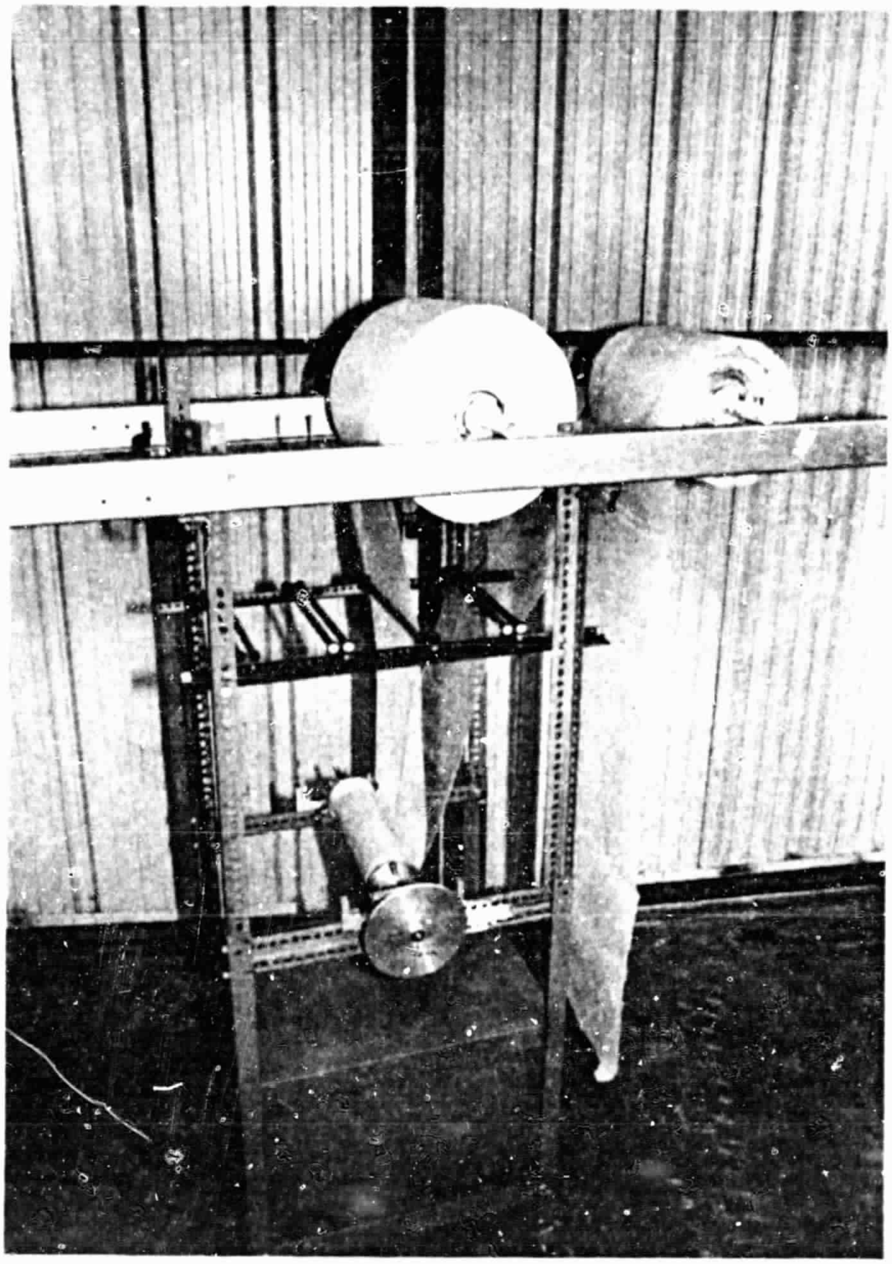

FIGURE 5-14
MULTI-PLY ROLLER: TWO PLY

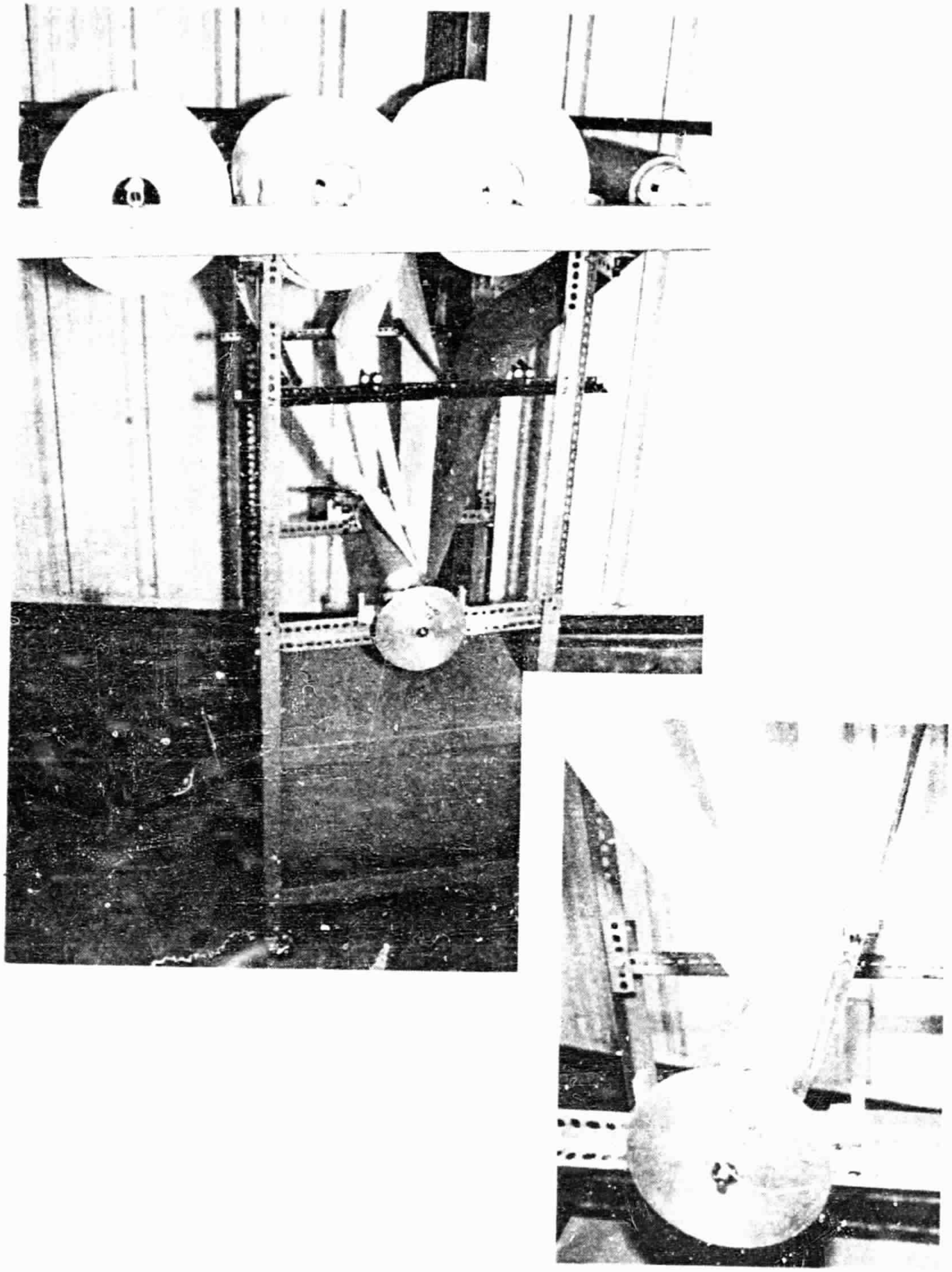

FIGURE 5-15
MULTI-PLY ROLLER: FOUR PLY

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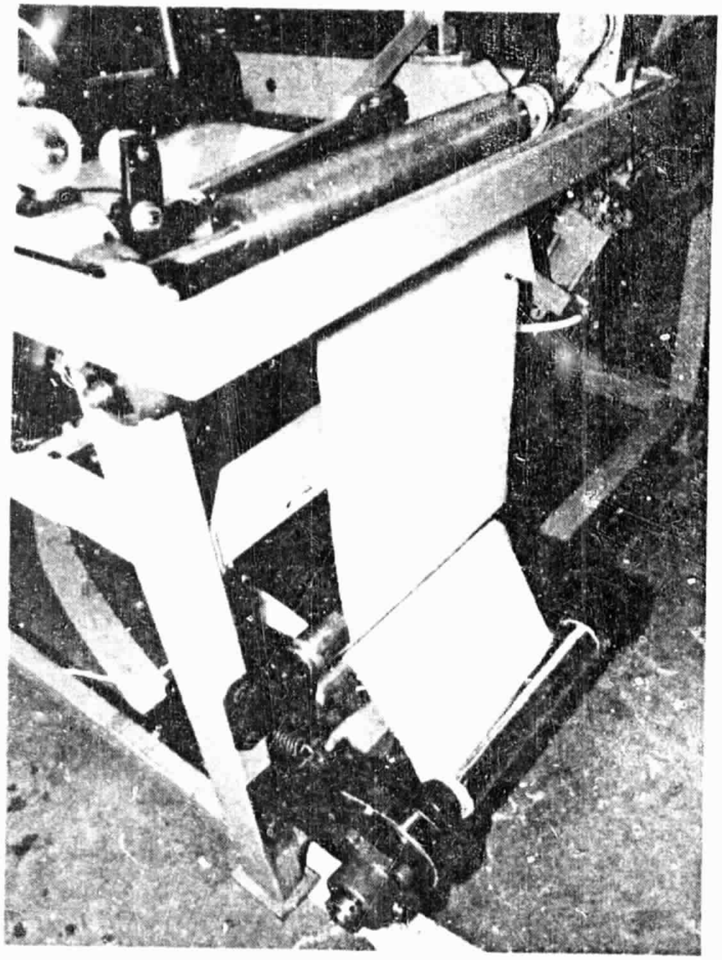

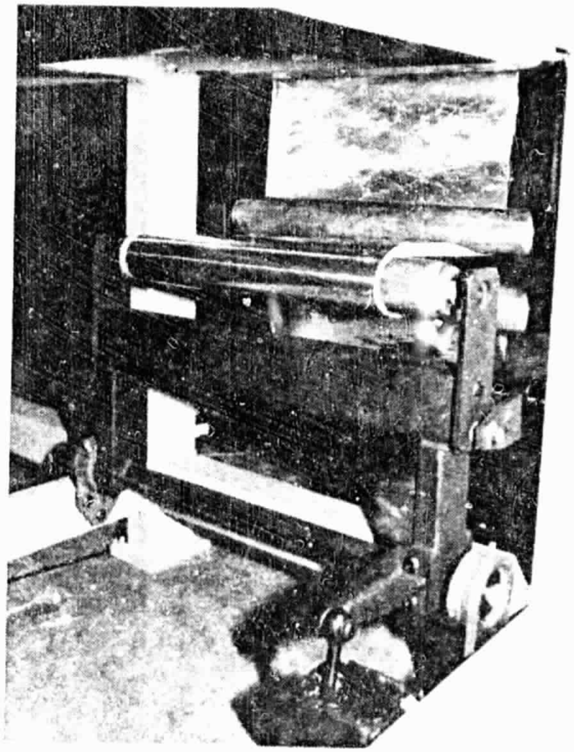

FIGURE 5.16
WEB TENSION CONTROL

of web control. First, the arm is spring loaded which applies the control tension to the web. Second, the position of the arm is used as feedback by the supply spool brake to maintain a constant web tension which it does in the following manner: if the web tension were to drop, the arm would pivot forward in the direction of the spring load. This motion applies the brake more increasing the web tension. Conversely, if the web tension were to rise, the arm would pivot back against the spring load releasing the brake some and thus lowering the web tension. It should be mentioned here that the brake is of the external compression strap type (similar to the "Rocky Mountain" brakes of early automobiles) with a $270^{\circ}$ wrap of brake lining around the drum. We have designed it to be self de-energizing which, although requiring greater activation forces, is a very smooth and progressive brake inherently free from chatter and lockup.

The final function of the dancer arm is to provide web storage during start-up and shut-down of the shuttle. The shuttle comes up to speed very quickly (a few miliseconds) and since some material is stored in the dancer loop, the only part of the web that **must** be accelerated with the shuttle is the length between it and the dancer roller. The mass of this small length is insignificant compared to that of the shuttle itself. After the shuttle starts, the web tension rises very quickly exceeding the desired level. To compensate the dancer arm moves the brake to the full off position which allows the supply spool to accelerate unimpeded. As the spool unwind speed approaches the shuttle's speed, the dancer moves forward gradually applying the brake until the correct web tension is reached. Since the shuttle's acceleration is rigidly defined by the stepper motor, we selected the other web tension design parameters (dance pivot length, brake diameter, spring preloads, etc.) to allow a full, 12" diameter supply spool to come up to speed in a few tenths of a second; a two-order-of-magnitude reduction over a directly attached shuttle and spool.

When stopping the shuttle, the opposite happens. The shuttle stops in, again, a few miliseconds but inertia causes the supply spool to continue unwinding. The web tension thus drops very quickly and the dancer moves all the way forward applying the brake fully. This stops the spool

and the material stored by the dancer during the stop is used for the next start.

The first test of the web feeding system used a hand-rolled 4-ply supply roll of mylar coated aluminum foil, Craneglas, white EVA, Craneglas (this roll is seen in Figures 5-12 and 5-16). The web tension was far too high (an estimated 60-70 lbs.) due to too much brake force. The springs that apply the preload to the brake were resized to get the web tension down to the desired levels. However, since the machine requires only very low web tension, the brake may not be required at all, i.e., the friction of the web passing over the three rollers seems to be sufficient to keep it under control. The brake could be eliminated and the dancer arm refitted with very light springs to perform only the start-up/shut-down storage function.

#### 5.2.2.7 Plumbing and Interconnections

An enclosure installed at the base of the framework (Figure 5-17) houses all of the solenoid valves, terminal strips and connectors.

Plumbing consists of inlet air fitting on the side of the enclosure which is connected internally to a manifold. This, in turn, supplies air to the inlet side of all of the solenoid valves. From there, various runs of polyflow tubing connect the valves to the cylinders.

The electrical interconnections are slightly more involved. There are five electrical connections to the enclosure, four of which can be seen in the Figure. The leftmost three connect the station to the control electronics, which are located in the cell stringing station's enclosure as described in Section 3.4.3. Incidentally, the same set of control electronics operates both the Automated Lamination Station and Automated Edge Seal Station. The discussion of the differences between these and the control system for the cell stringer will be discussed in Section 6.3.

The cable that attached to round black connector carries feedback signals from the limit switches back to the control system. The rectangular connectors next to it carry the command signals from the driver board.

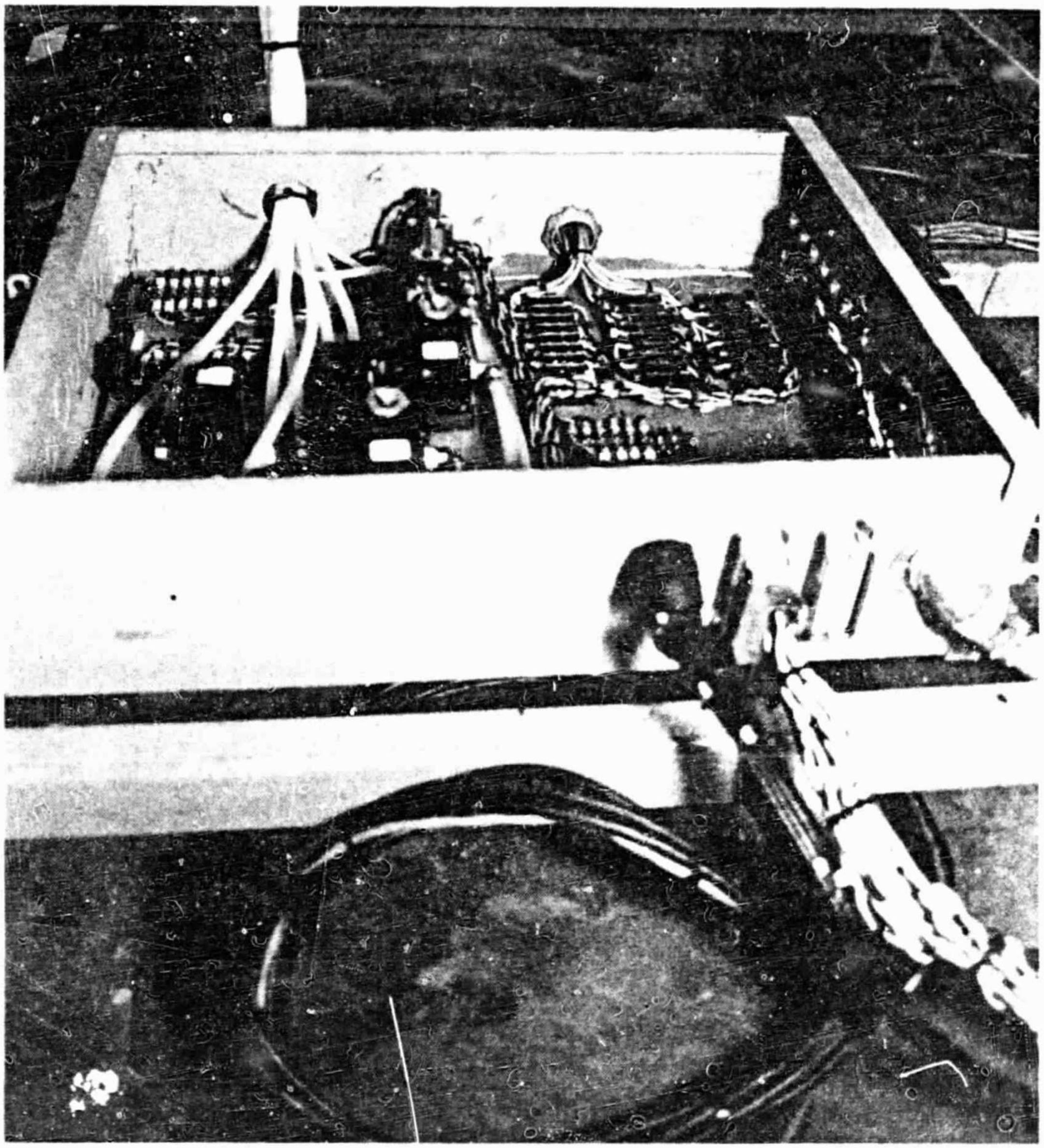

FIGURE 5-17
LAMINATION STATION JUNCTION BOX

Inside the enclosure, these connectors branch out to a series of terminal strips which can be seen directly behind the connectors. From here the wires are either connected directly to devices in the enclosure (the solenoid valves and the solid state relays (SSR) that control the chamber heater) or exit out the back of the enclosure to operate the stepper motors.

The rectangular connector with the cable plugged into it is for operating the Layup Station. The cable is switched to the other receptacle when the vacuum chamber is in operation. Out of view around the corner is a hardwired cable which carries the power from the SSR's up to the chamber. It also carries the command signal for the vacuum control solenoid located in the chamber.

The rightmost connector in the figure is another hardwired high current (60 A) line which provides the input power for the SSR's.

## 5.3 Lamination Chamber

Figure 5-18 illustrates the original design concept for the Automated Lamination Chamber.

The design is based on the chamber developed by Tracor MBA under JPL contract 955281. The internal dimensions are 13"x49"x1/2" deep which allows 1/2" clearance around all sides of the 1'x4' panel.

The chamber proper is a piece of 1/4" thick aluminum sheet with 1" diameter thickwall aluminum tubing welded around the edge like a picture frame. The tubing plays the dual role of being the chamber sides and vacuum manifold. Small holes drilled into the tubing form the vacuum inlets.

The chamber sits on a box-like framework which both improves its torsional rigidity and provides an area to mount the cover opening mechanism, vacuum control solenoid, and all attendant wiring and plumbing.

Heat is supplied by a one-piece, 1'x4' flexible heating element attached to the underside of the aluminum sheet.

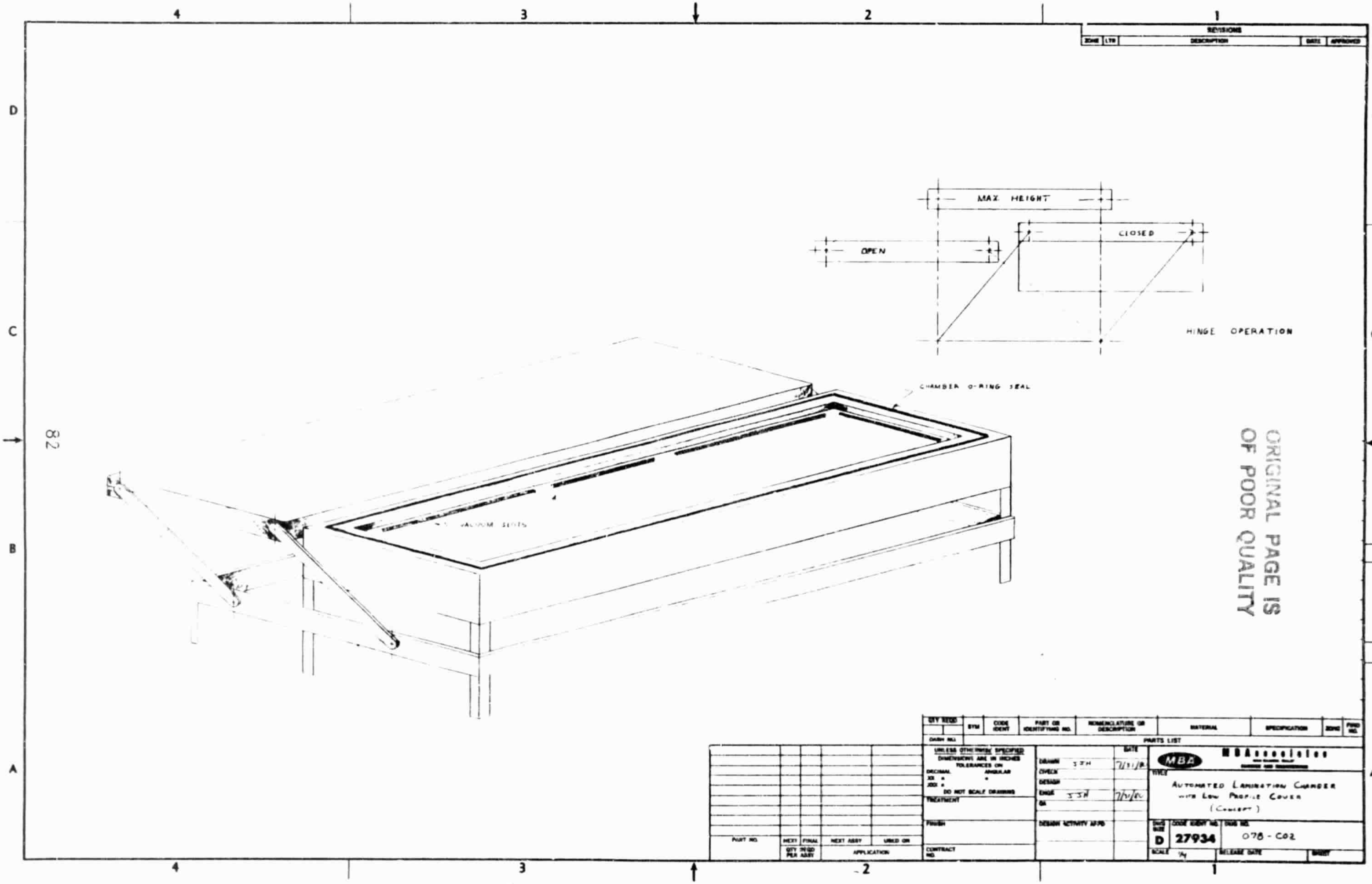




FIGURE 5-18
AUTOMATED VACUUM CHAMBER CONCEPT

### 5.3.1 Chamber Cover

The chamber cover is based on the "vacuum bag" principle as was the cover of the previously developed chamber mentioned above. For that chamber, the cover was simply a 1/4" thick sheet of silicon rubber that reached to the outer edge of the chamber walls. Pieces of angle were placed along the edge of the sheet and clamped in place with spring clips. A film of vacuum sealing grease served as the seal. This arrangement was able to sustain the minimum 27 in Hg required for lamination.

Two new cover concepts were developed for the chamber used on this program. The earlier rigid frame, hinged cover concept, as shown in the Figure was replaced in favor of a rather novel all soft frameless design. Unfortunately, the "soft top" concept could not be made to operate satisfactorily within the time and budget constraint imposed; so we returned to the original concept, although in a less automated manner.

Both designs have distinct advantages, hence are both presented.

#### 5.3.1.1 Original Cover Concept

The cover in this concept consists of a metal framework surrounding the rubber sheet. This both supports the sheet and provides the mating surface for the vacuum seal. This seal is a permanent O-ring or soft rubber type mounted on the vacuum chamber walls. The majority of the cover area is still the flexible rubber sheet as is required by the "vacuum bag" concept.

Connecting the chamber body to the cover is a hinge upon which were placed several design constraints resulting in the chosen configuration as shown in the figure.

The main constraint is that, in the open position, the cover must lie flat and the top of the cover be at least level with the top of the chamber body and preferably lower. This is to allow clearance for the chamber to pass under the Lamination Layup Station.

The most straightforward way of doing this is to attach the cover by means of a continuous or "piano" hinge along the back such as with a tool chest. There are several drawbacks to this design, however. First, a large vertical clearance is required to allow the cover to swing open. Second, it is difficult to actuate in an automated manner since the center of gravity of the cover follows a similar large arc. This means that the moment reactions at the hinge (where the actuators would have to be attached) would be very large to start opening the cover, drop to zero at mid travel, and be very large the opposite direction to stop the cover. A third problem is that until the last instant of closing, the cover is not parallel to the chamber body. This means that the sealing distances and forces are uneven being heavy along the back and light along the front. A final drawback is that the cover inverts every time it is opened. This would have an unknown effect on the rubber diaphragm flexing back and forth.

To avoid these problems, it was obvious that the cover should be opened vertically a short distance, moved away horizontally and dropped back down once it is clear of the chamber. One possible way to do this is with a non-linear slide such as used on the side doors of helicopters and delivery vans. However, investigations into these devices showed them to be rather intricate precision mechanisms not really in keeping with the design philosophy of this project.

A more elegant solution is a simple 4-bar linkage with the chamber cover and body forming two of the links as shown in the Figure. It is mechanically much simpler than a slide while retaining the advantages of low maximum height and keeping the cover parallel to the body at all times. Additionally, it has the further advantage of allowing the cover to be dropped as low as desired when opened. Finally, it is very easy to actuate with either rotary actuators at the pivot points or linear actuators acting on the links. Torsional springs installed at the pivots would support the cover when open and preload it when closed to ensure a good vacuum seal.

5.3.1.2 Frameless "Soft Top" Design

In the first chamber design sessions, the cover concept was modified by replacing the hinge links and frame with a "roll top desk" arrangement (Figure 5-19). This consists of lengths of tubing attached lengthwise across the silicon rubber cover connected at the end by extended-pitch roller chain. Large sprockets simply roll the cover up to open the chamber.

To automate the cover opening and closing, a loop of Berg chain (a light-weight industrial chain consisting of small diameter stainless steel cables with high strength plastic rollers) was attached to both ends of the large chain and passed over the drive sprocket. There is a continuous loop of chain around both ends of the chamber so that the cover is opened and closed in much the same manner as a curtain rod.

The advantage of this arrangement is that the vertical clearance required to open the cover is reduced to zero. This means that the chamber can be opened while it is inside the layup station's framework so that the chamber-opening mechanism could be mounted on the framework rather than on the chamber itself. The rationale behind this is twofold: First, in a production situation, it greatly reduces the number of parts needed. On a production line there could be up to 100 chambers for each layup station. Mounting the chamber opening mechanism on the layup station rather than the chamber reduced the number of mechanisms required by 100 to 1. Second, and more subtly, it allows the chamber to be unpowered while in the station. The chamber has power and control cables and a vacuum line attached. If the layup station is being used in a pass-through mode (the chambers can either pass completely through the station, as on a conveyer belt, or can be inserted and removed from the same side) these lines would have to be disconnected to allow passage through the station leaving the chamber powerless.

Since we are not in a production situation, for simplicity of design and construction, we mounted the cover motor on the chamber itself.

5.3.1.2 Frameless "Soft Top" Design

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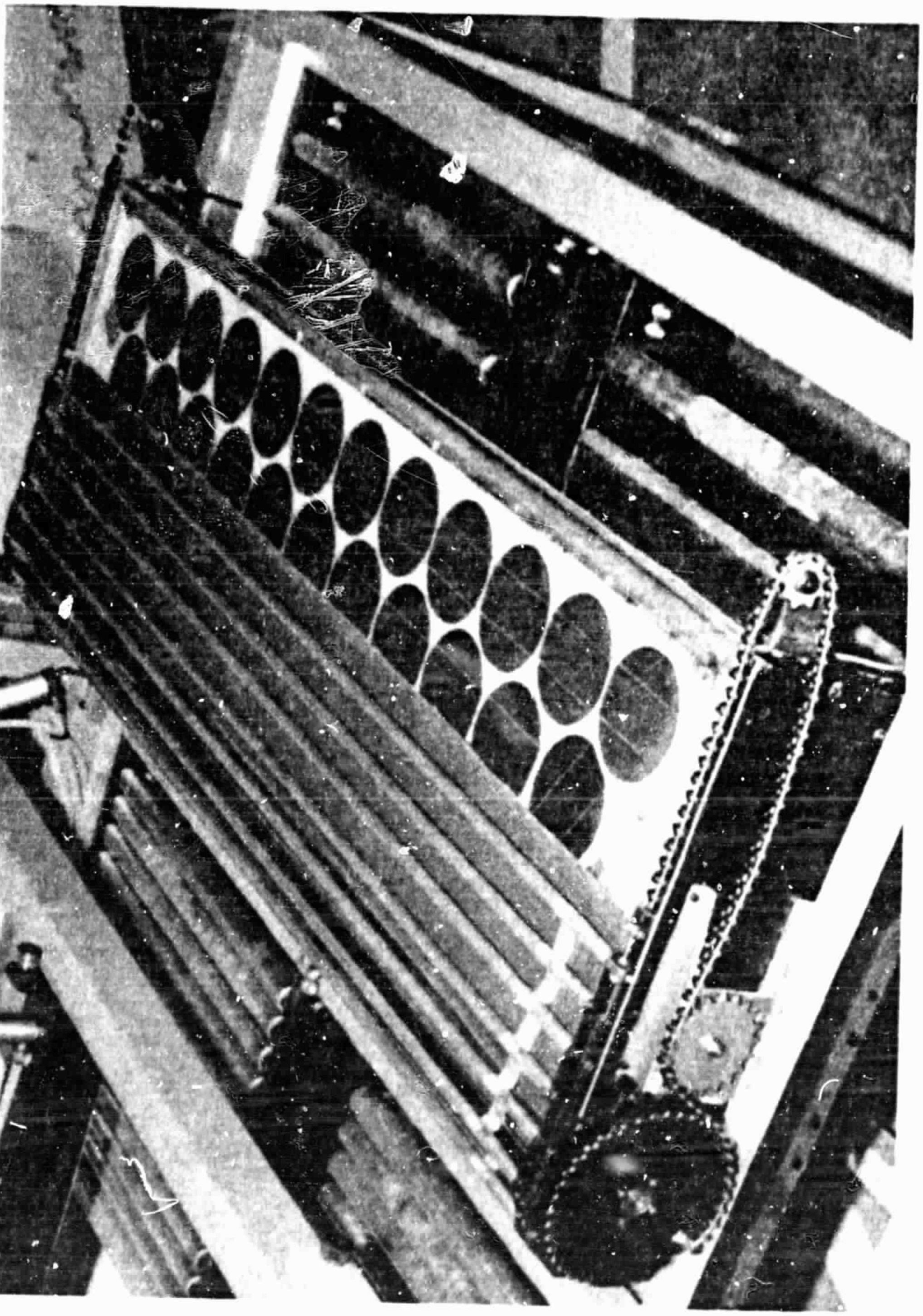

FIGURE 5-19
VACUUM CHAMBER FLEXIBLE COVER

The 1/8" thick silicon rubber sheet originally used to form the chamber cover proved to be too stiff to make a good seal when the chamber was first vacuum tested, even with extensive clamping around the edge. Since the chamber must be self sealing with no help from clamps or other aids, a three-pronged solution to the problem was devised. First, the top (sealing) surface of the "picture frame" tubing was fly cut to both increase the available surface area and to ensure a uniform sealing surface. Second, the rubber sheet was reduced to 1/16" thick to help it conform to the chamber's shape. Lastly, the new sheet was of a softer compound (40 Durometer instead of 50) to aid in its flexibility.

This solution worked well enough to cause another minor problem. With the new rubber sheet simply lying on top of the chamber (i.e. with no clamping or any other aids) when the vacuum was applied, the sheet would be sucked down conforming to the various shapes of chamber and module, much like a vacuum forming process. In fact, it conformed so well that the sheet was pulled into the gap between the module and frame tube cutting off the vacuum to the module! The solution to this was to cut shallow slots (1/16" deep) in the floor of the chamber from a point underneath the module over to the vacuum hole in the frame tube. In this way, even if the sheet is sucked completely to the floor of the chamber, it won't be able to conform to the sharp edges of the slot and the vacuum path to the module will remain unrestricted.

These early tests were quite encouraging showing that a plain rubber sheet could be self-sealing and have good draw-down. Unfortunately, the chamber vacuum could not be pulled below 20 in-Hg with this arrangement, far short of the 27-28 in-Hg required for encapsulation. The reason for this inadequate performance is implicit in the last paragraph, i.e., the rubber sheet could not conform completely to the sharp corners of the chamber. In fact, the 20 in-Hg level was achieved only after extensive recontouring of the corners to make the transition more gentle.

Despite the fact that this concept could not be made to work within our time and budget limitations, Tracor MBA feels that its inherent advantages make it worthy of continued study. An obvious direction to try is to replace the flat rubber sheet with one that has a molded ridge that conforms to the sealing surfaces of the chamber.

5.3.1.3 Final Cover

In order to make the chamber operational to allow us to produce the deliverable modules, a rigid frame was built (Figure 5-20) which is placed on top of the rubber sheet so that the edge of the sheet is compressed between the frame and the chamber walls. Four toggle clamps placed along the long sides of the chamber hold the cover in place. However, this meant removing the automated cover opening mechanism as the tubular supports would have been in the way. This renders the opening and closing of the chamber a manual operation as there was neither time nor budget left to automate this new cover. It should be noted, though, that the new cover design is very similar to the original concept as described in Section 5.3.1.1 and that preliminary designs for automating the cover therefore exist.

Even though the chamber cover is no longer automated (actually this was not a contractual requirement. but rather was done in the spirit of the program i.e., totally automating the process) the process cycle is completely automatic. This includes the controlled pump-down (to avoid cell breakage), rapid heat to cure temperature, holding at cure temperature for the correct duration, cool down and finally vacuum release.

5.3.2 Process Control and Instrumentation

Since the chamber is of automated design, a certain amount of feedback instrumentation is required. However, due to the very flexible nature of our control system, this can be kept to a minimum. Feedback instrumentation consists of a vacuum transducer connected to the manifold to monitor chamber pressure and a small number of thermistors to monitor temperature. Control equipment involves only a solenoid valve to regulate

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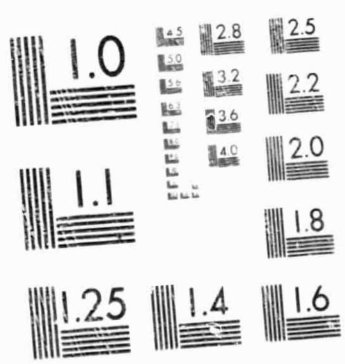


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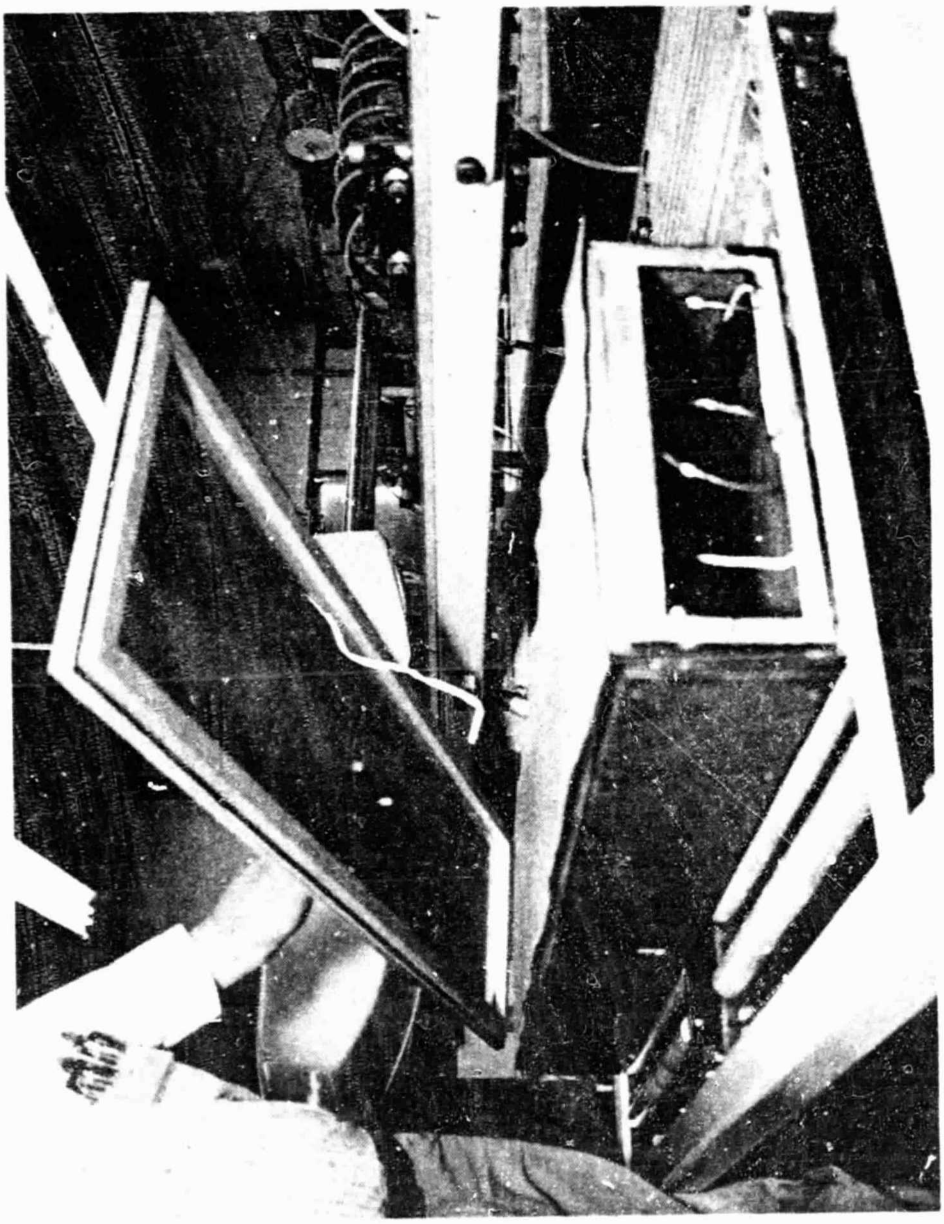

FIGURE 5-20
LAMINATION CHAMBER RIGID COVER

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chamber pressure and some high output power transistors to supply power to the chamber heater. Power connections are made through the Lamination Station's junction box as described in Section 5.2.2.7. The control system command cable is plugged into the third receptacle from the left in Figure 5-17. The high current cable is connected to a receptacle on the chamber sidewall. This supplies power to both the chamber heater and vacuum control solenoid. Feedback from the thermistor and vacuum transducer are output to a round connector on the chamber identical to the one on the far left of Figure 5-17. During chamber operation, the feedback cable is transferred from the junction box to the chamber.

## 5.4 Multiple Chamber Study

Our Automated Lamination System is based on the concept of a single, high-speed (1 module/min.) layup station combined with a large number of modular encapsulant curing chambers. In a production situation at least 60 of these thermal/vacuum curing chambers would be interfacing with the single chamber loading/unloading machine. (At present, a one hour cure cycle to evacuate, heat, hold for cure, and cool seems quite feasible, based on current JPL research).

To complete this concept, it was required that we identify production-feasible methods of cycling large numbers of modules through the curing cycle at the specified thruput rate.

As with most production processes, a high volume curing system can be of two types: continuous or batch. A candidate system for each is discussed.

### 5.4.1 Continuous Curing

Figure 5-21 shows a viable concept for continuous curing of modules using discrete chambers. They are placed on a carousel which circulates through the Lamination Layup Station and are loaded and unloaded by the robot. In the center is the equipment for supplying power (for heat) and vacuum for each chamber. Also in the center is the control equipment for cycling each chamber independently.

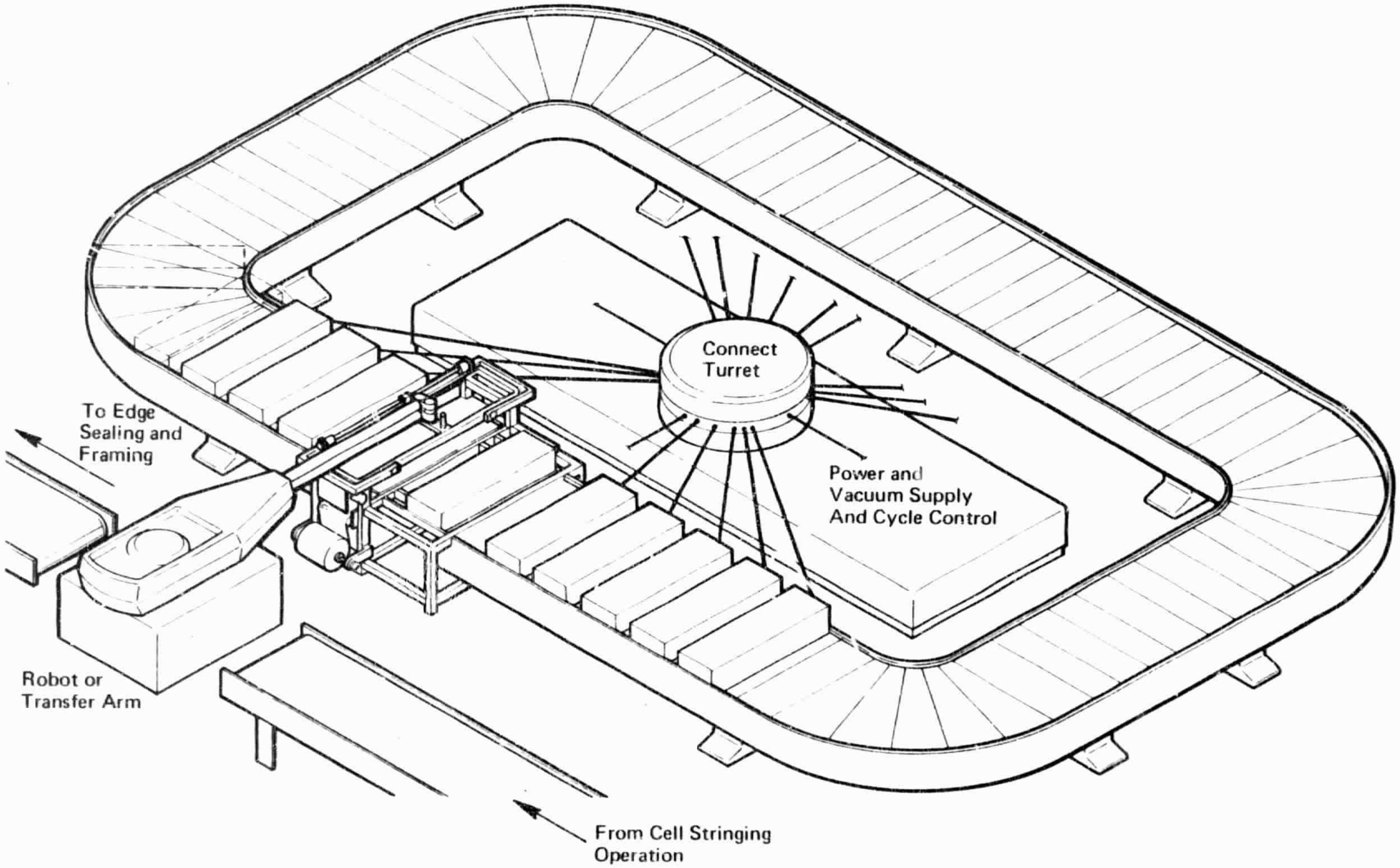


FIGURE 5-21
CONTINUOUS CURING CAROUSEL

A major consideration is to minimize the floor space required. If the 1 ft. wide chambers are spaced 1 ft. apart, then 60 chambers require (1+1) x 60 = 120 linear ft. of carousel.

A circular carousel with a mean diameter of 40 ft. would do it but the floor area required would be 1520 $ft^2$ based on an outside diameter of 44 ft.

A straight sided, round ended carousel (such as used for luggage at airports) with 35 ft. long sides spaced 16 ft. apart has sufficient length and occupies only 1014 $ft^2$ based on outside dimensions. This still leaves a 12'x35' space in the center for control equipment.

### 5.4.2 Batch Curing

An alternative to continuous curing is batch curing which can be done by a system similar to that in Figure 5-21. Considerable floor space can be saved with this system, however, as the carousel is replaced by a linear conveyor which runs from the layup station to a pair of batch processing chambers.

Rather than laying up into an individual chamber, the module is built up directly onto the conveyor surface. For a superstrate design, the glass is laid down first and the module built face down from the top down. For a substrate design, the bottom (substrate) layer is placed down first and the module built face up from the bottom up. After the materials have been placed, the conveyor moves them to the batch chambers.

A minimum of two chambers are required, each holding one "cure cycle's worth" (in this case one hour) of output from the layup station. In this way, while one chamber is cycling, the other is being unloaded/reloaded. As presently conceived, these chambers would have a large number of racks, such as with large commercial ovens. Each module position would have a diaphragm above it to supply the pressure required for lamination.

## 6.0 PHASE FOUR: EDGE SEAL AND FINAL ASSEMBLY

The goal of this phase is to take the encapsulated modules, such as would be removed from the lamination chamber at the end of its

cycle, and turn them into field-installable solar panels.

This requires, at the minimum, edge sealing, framing, and the attachment of (or installment into) a field support structure.

Our approach was to use MBA's Glass Reinforced Concrete (GRC) as a combination substrate, edge frame and support structure. A 4'x8' GRC panel design was developed by MBA for JPL under contract #955281 which was the basis for the panel used for the deliverables on this contract.

The GRC panel has a 1/4" deep indentation on the surface which acts as an edge frame and allows the module's glass surface to be flush with the panel's concrete edge.

The edge seal (a hot melt Butyl) must be applied by a machine that has controlled rectilinear motion.

Figure 6-1 is the original concept sketch of the machine necessary to meet these requirements. The hot melt applicator is held in a fixture that allows it to be moved over the GRC panel in both the X and Y axes independently.

One of the details discussed when setting up the requirements for the deliverables was whether the GRC panel would be large and accommodate several modules such as shown in the figure, or be able to accommodate only one module each. This latter form would be for feasibility demonstration only since such a configuration would have very poor array packing densities.

It was decided that the machine should have the capacity to do a 4'x8' (which is becoming an industry standard) but that the actual deliverables would probably be smaller for ease of portability.

## 6.1 Sequence of Operations

The general sequence of operations for the edge seal machine (processing eight 1'x4' modules per GRC panel) is:

1) The edge sealant is applied along the three sides of the GRC panel where the edges of module #1 will make contact.

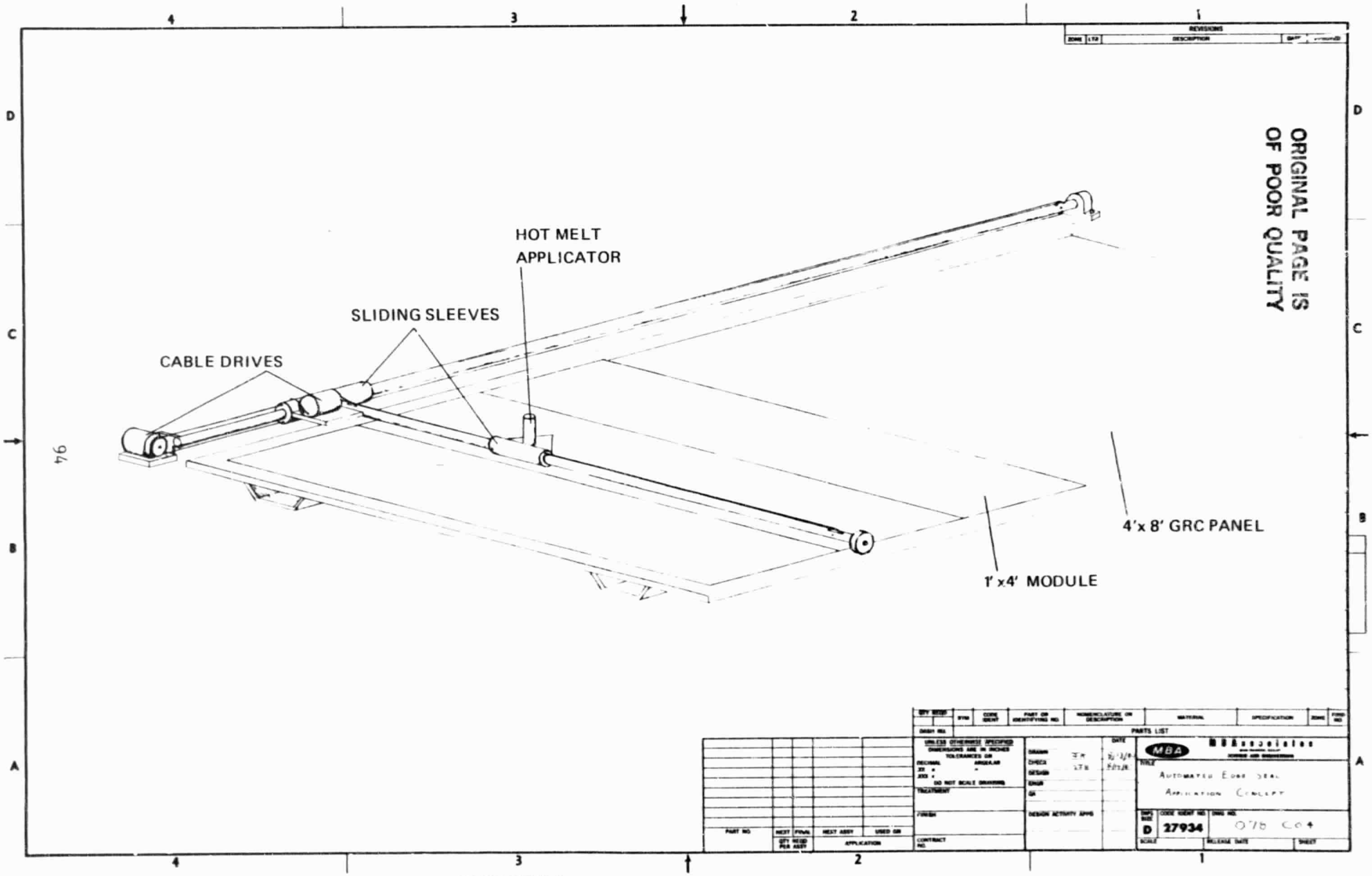


FIGURE 6-1
AUTOMATED EDGE SEAL APPLICATION CONCEPT

2) Module #1 is placed into the GRC panel by the robot.

3) Edge sealant is applied to the panel where the two short sides of module #2 will make contact and along the fourth side of module #1 where the two modules join.

4) Module #2 is placed into the GRC panel by the robot.

5) Steps 3 and 4 are repeated five times for modules 3 thru 7.

6) Edge sealant is applied to all four sides of the remaining opening in the GRC panel.

7) Module #8 is placed into the GRC panel by the robot.

8) The panel is removed for attachment of electrical hardware followed by packing and shipping to the installation site.

9) A new (empty) GRC panel is put in place and the cycle starts over.

The cycle time of the Edge Seal machine would be tied to that of the encapsulation station, i.e., approximately one minute per module or eight minutes for a 4'x8' panel.

It should be noted that while a 4'x8' panel is the maximum size that the machine can process, there is no limit to either the minimum size or graduation of the sizes. Being driven by stepper motors controlled by an interactive computer, the machine can handle any size or shape panel within the resolution of the steppers. Of course, rectangular panels are better suited as the control system's digital nature may become apparent if it tries to follow odd angles or compound curves.

## 6.2 Hardware Development

This station had a relatively short development period as a large number of standardized components could be used.

The machine is composed of three components: shuttle, carriage, and frame. An explanation and description of these components follows. Figure 6-2 is a general view of the completed machine with a 2'x4' GRC panel in position for processing.

### 6.2.1 Frame

Since the Edge Seal machine was designed to apply a hot melt seal to multiple modules (up to eight 1'x4'), the simplicity of inserting and removing GRC panels had to be considered. A standard industrial roller conveyor was decided upon to roll GRC panels into position and provide the basic frame for the rest of the machine.

The frame is the support on which the carriage travels back and forth. The frame has no moving parts, other than the unpowered conveyor rollers.

### 6.2.2 Carriage

The carriage supports the tracks upon which the shuttle rolls. The carriage itself is mounted on rollers which move along tracks on the frame perpendicular to the shuttle. Figure 6-3 shows the carriage sitting in position on the frame with the shuttle, in turn, on it.

The main purpose of the carriage is to move the shuttle along the Y Axis* on top of the frame. The carriage "crawls" along the frame by using a sprocket and chain arrangement driven at both ends via a drive shaft. It has floating rollers on one end to allow for misalignment of the frame. The chain that both the shuttle and carriage "crawl" on is Berg chain, identical to that described in Section 5.3.1.2.

* X axis refers to the 4' length of the GRC Panel, Y axis is the 8' length.

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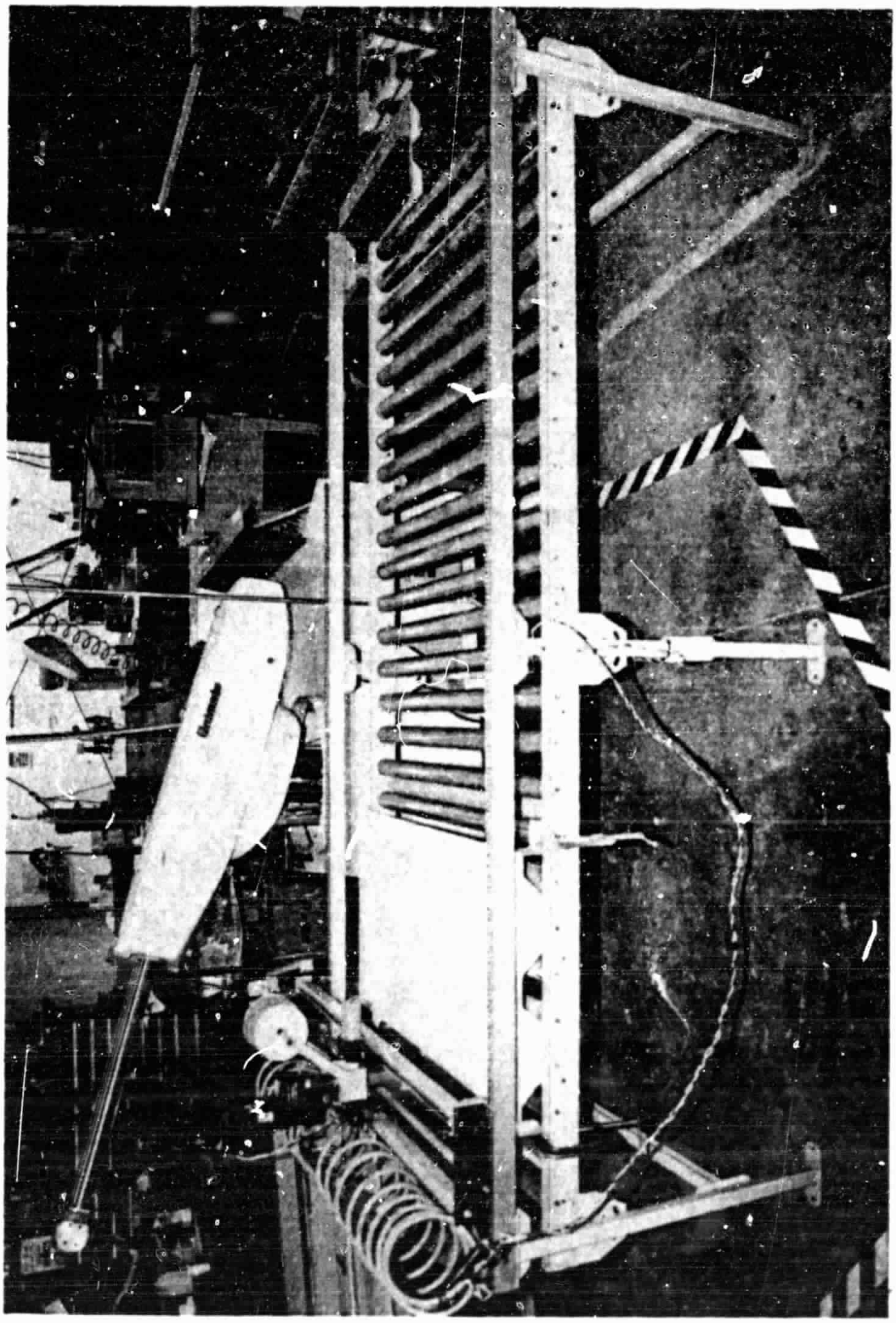

FIGURE 6-2
AUTOMATED EDGE SEALER

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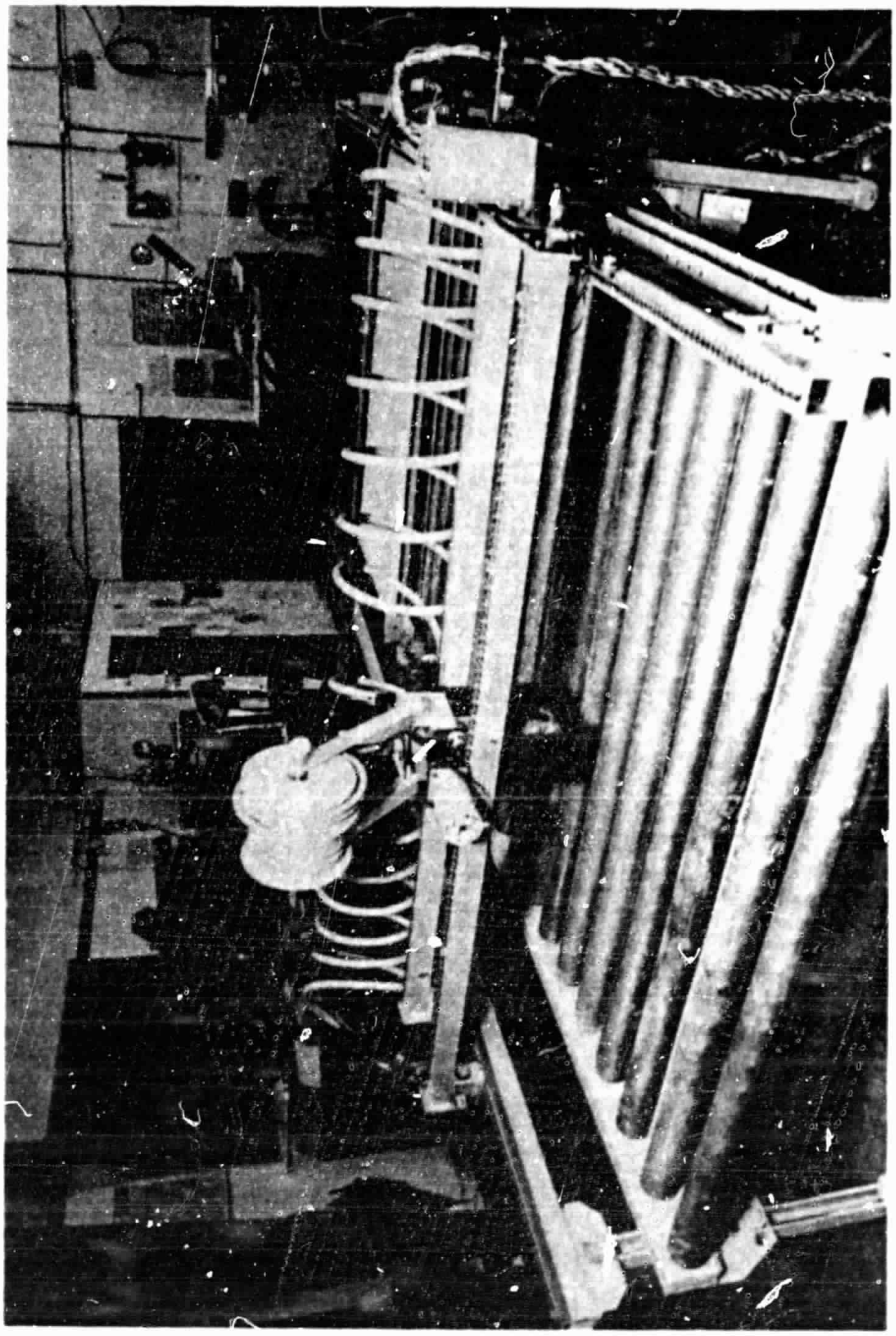

FIGURE 6-3
EDGE SEALER CARRIAGE

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### 6.2.3 Shuttle

Figure 6-4 shows the shuttle sitting on top of the carriage. The purpose of the shuttle is to hold the hot melt applicator secure while moving in a controlled linear motion. The shuttle is powered by a horizontally mounted motor, and "crawls" along the X axis by using a sprocket and chain arrangement. To allow for misalignment of the carriage tracks, fixed rollers were used on one side of the shuttle and floating rollers on the opposite side.

### 6.2.4 General

A novel method to control the cables as the shuttle moves across the panel was developed. The two sets of wires (one set for the drive motor and one set for the hot melt gun) are each run through a piece of 1/2" ID coiled air hose. These are then supported on either side of the shuttle in a manner that allows the hose to uncoil as the shuttle travels across the panels (Figure 6-5). When the shuttle returns, the hose, being self storing, simply coils up out of the way.

Tests were run that drive the hot melt gun both in rectangles (i.e. running the X axis and Y axis motors individually) and along diagonals (running both motors simultaneously). To expand on that last point; actually the control system cannot run both motors at the same time. Instead, the software routines that run the motors are set up to operate each motor for only one step (1/200 of a revolution or 0.04" of travel) at a time. These are then placed in a loop to control the number and speed of the steps. The speed of the computer's execution is such that the motion is indistinguishable from true simultaneous operation.

The hot melt gun was tested to determine two important operating parameters: the extrusion rate of the bead and the consumption rate of the Butyl supply rope. The results turned out to be an almost exact 2:1 ratio with the bead extruded at approximately 2 in/sec and the supply rope being consumed at 1 in/sec. The supply spools are approximately 50 ft. each meaning that 100 ft of bead could be extruded from each spool. This is sufficient to edge seal two 4'x8' panels consisting of eight

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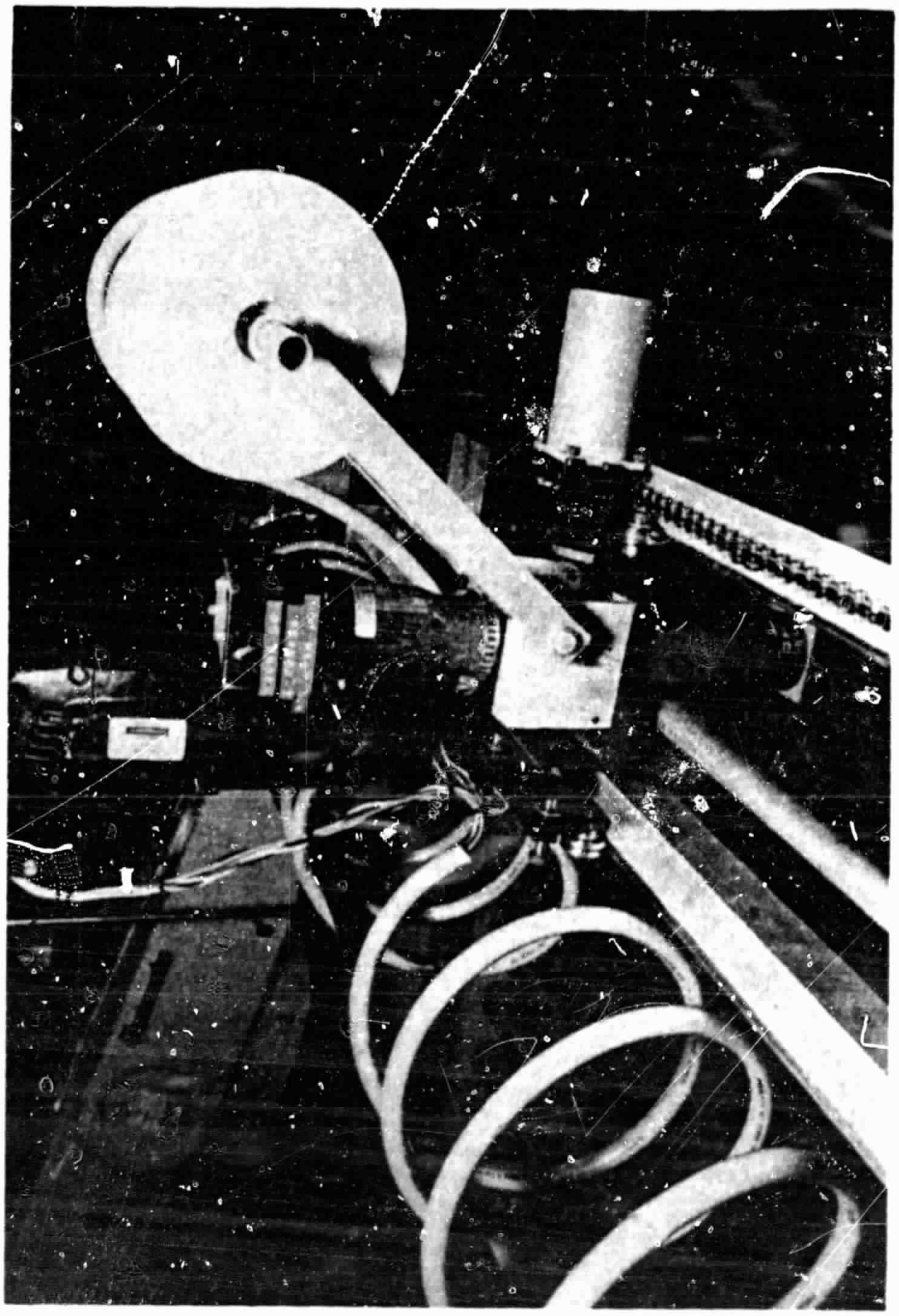

FIGURE 6-4
EDGE SEALER SHUTTLE

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1'x4' modules each.

### 6.3 Control Electronics

The same set of control electronics is used to control both the Lamination Station and Edge Sealing machine. They are basically the same as those that control the previous cell stringing station but with some important differences. They consist of an interface board which converts the computer's output data into discrete on/off commands, a high current driver board which amplifies these low level commands to operate solenoid valves and stepper motors and finally, an isolator board which is placed between the other two to protect the delicate interface board from any high current surges. The interface board also contains small reed relays to interface with the Unimate robot. All of this equipment uses the same circuit designs as that on the cell preparation station.

Since the control requirements for this equipment are identical for all of the new machines, and since they will never be operated at the same time, as a matter of economy and expediency, we used the same set of electronics for all three new machines (from a control standpoint, the Lamination Chamber is considered a separate machine). Quick disconnectors were used so that the cables could be easily switched. In a production situation, of course, each machine would have its own controller and even in our case separate computer programs for each of the three machines are required.

There are some additional electronics involved with these three new machines to handle requirements not encountered with the original cell stringing system. First is the ability to handle AC line voltage at high current. On the Lamination Chamber, this is necessary to run the chamber heater.

On the Edge Sealing machine, both the hot melt gun heater and feed motor (not to be confused with the shuttle and carriage drive motors which are DC steppers) run on AC. This requirement is met by high current solid state relays (SSR) which are operated by the existing driver transistors.

The other new requirement pertains to the Lamination Chamber only. The chamber has many analog sensing elements (thermistors and a vacuum transducer as detailed in Section 5.3) whose signals must be converted to digital to be understood by the computer. Rather than hooking up each sensor to its own A to D convertor (which are quite expensive) we are using a multiplexer to scan the sensors on a time sharing basis. The multiplexer we are using (a Motorola 14051) can handle up to 8 inputs at one time and output them to a single A to D convertor in a controlled fashion.

Control routines were written for each individual function on the new machines, e.g., shuttle drive, shear solenoid, etc. Each function could then be operated from the computer keyboard simply by giving the RUN command for the appropriate routine. The generalized controlling program was then created by placing all of the individual function routines in the correct order separated by timing waits. The duration of these waits is determined empirically making this (naturally) a repetitive and time consuming process.

## 7.0 PHASE FIVE: FABRICATION

This phase is fairly self explanatory. It requires the fabrication of six $4ft^2$ modules ready to be installed in the field. The cells are to be laid up and interconnected using the equipment developed during the previous contract (and improved during this one). The inter-connected cells are to be encapsulated, edge sealed and framed using equipment developed during this contract.

### 7.1 Deliverable Specifications

It was decided early in the program that the module size would be 1'x4' and that the composition would be the Spectrolab laminate as described in Section 5.2 and illustrated in Figure 5-4. The cell circuit would be patterned after an older ARCO design with 35 series connected cells in three rows of twelve-eleven-twelve. There is an output connector at each end; i.e., no bus bars, just end tabs.

In order to demonstrate the multiple-size capability of the

Final Assembly Station, these six modules have to be laid up on at least two different size GRC substrates. The final size of the substrates was not decided upon until fairly late in the program. For ease of portability during JPL testing it was decided to keep the overall size small. The final deliverable panels are a combination of 1'x4' (one module per panel) and 2'x4' (2 modules per panel) substrates. Figures 7-1 and 7-2 are design sketches of the 1'x4' and 2'x4' GRC panels respectively.

As mentioned in the previous section, these panels are based on a 4'x8' panel developed under a previous contract. Since time and budget constraints did not allow a full stress analysis of the design, it was decided to err on the conservative side and retain the full sized trapazoidal stiffening beam on both panels (one on the 1'x4' and two on the 2'x4') rather than scaling it down. As this beam was designed to provide adequate stiffness to the much larger 4'x8' panel, these small panels are somewhat over designed for strength. Another small change from the 4'x8' design is that the new panels have a 1" wide raised lip around their perimeter which acts as an edge frame whereas the larger panel was flat.

The actual fabrication of these panels was sub-contracted to a local firm that that has GRC spraying equipment and specializes in prototype runs. This provided a considerable savings to the program as the major cost of any short run GRC fabrication involves the setup and breakdown (and in our case refurbishment) of the spraying equipment. Since this vendor is already set up for short runs, we paid only for the materials and labor involved with the actual spraying of the panels. The molds used in the fabrication were built and checked by MBA before being shipped to the vendor.

The extra strength inherent in this design allowed us to take advantage of another advance. Despite all of its advantages, the big drawback to GRC panels, compared to more conventional array structures, is weight. This vendor has perfected a series of lightweight GRC materials that trade off weight for strength. They range from the immensely strong, but very heavy, standard GRC, usable as a structural material, to a very light, air filled version suitable only for decorative castings such as artificial brick. Our panels were made from a middle weight material that replaces the sand

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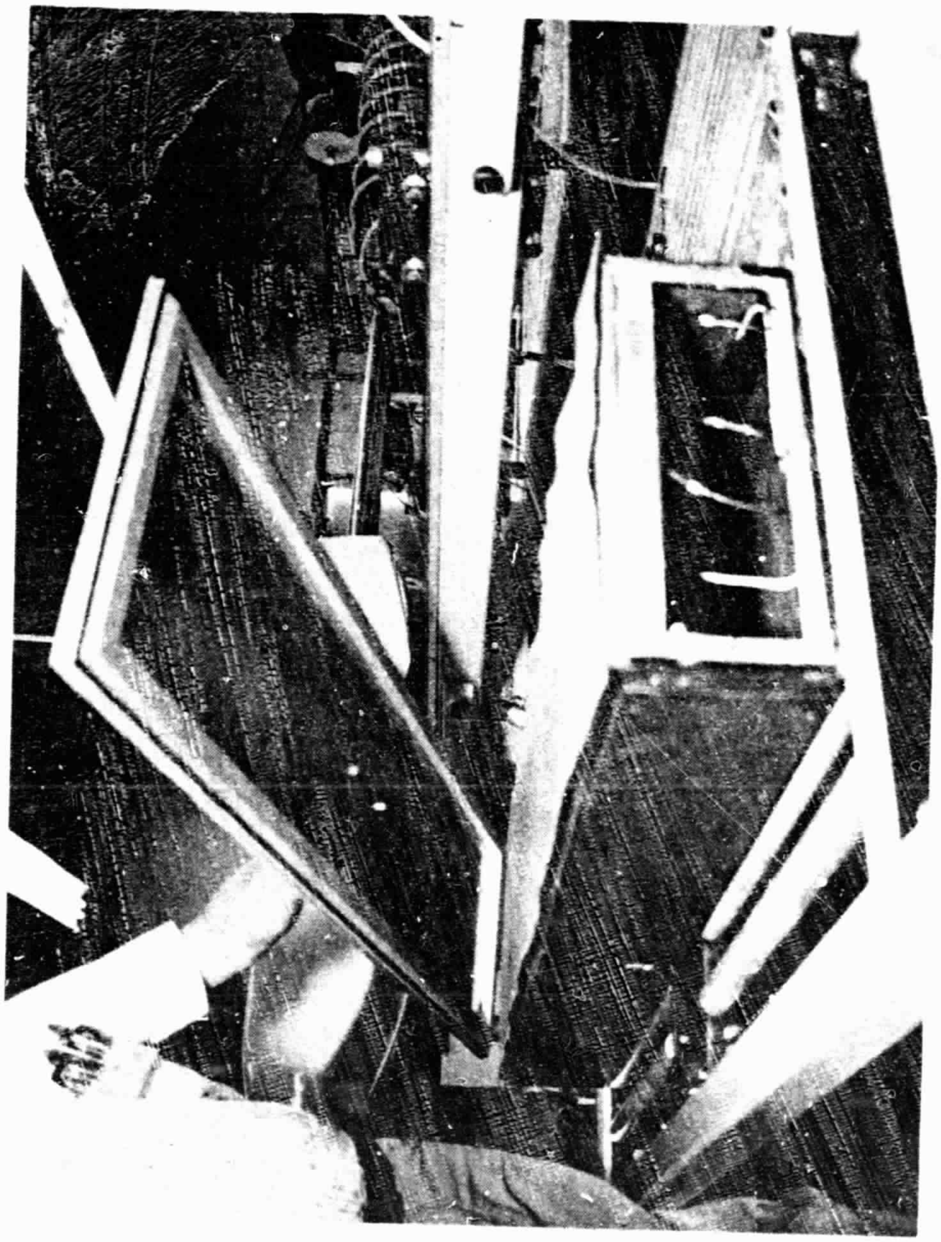

FIGURE 5-20
LAMINATION CHAMBER RIGID COVER

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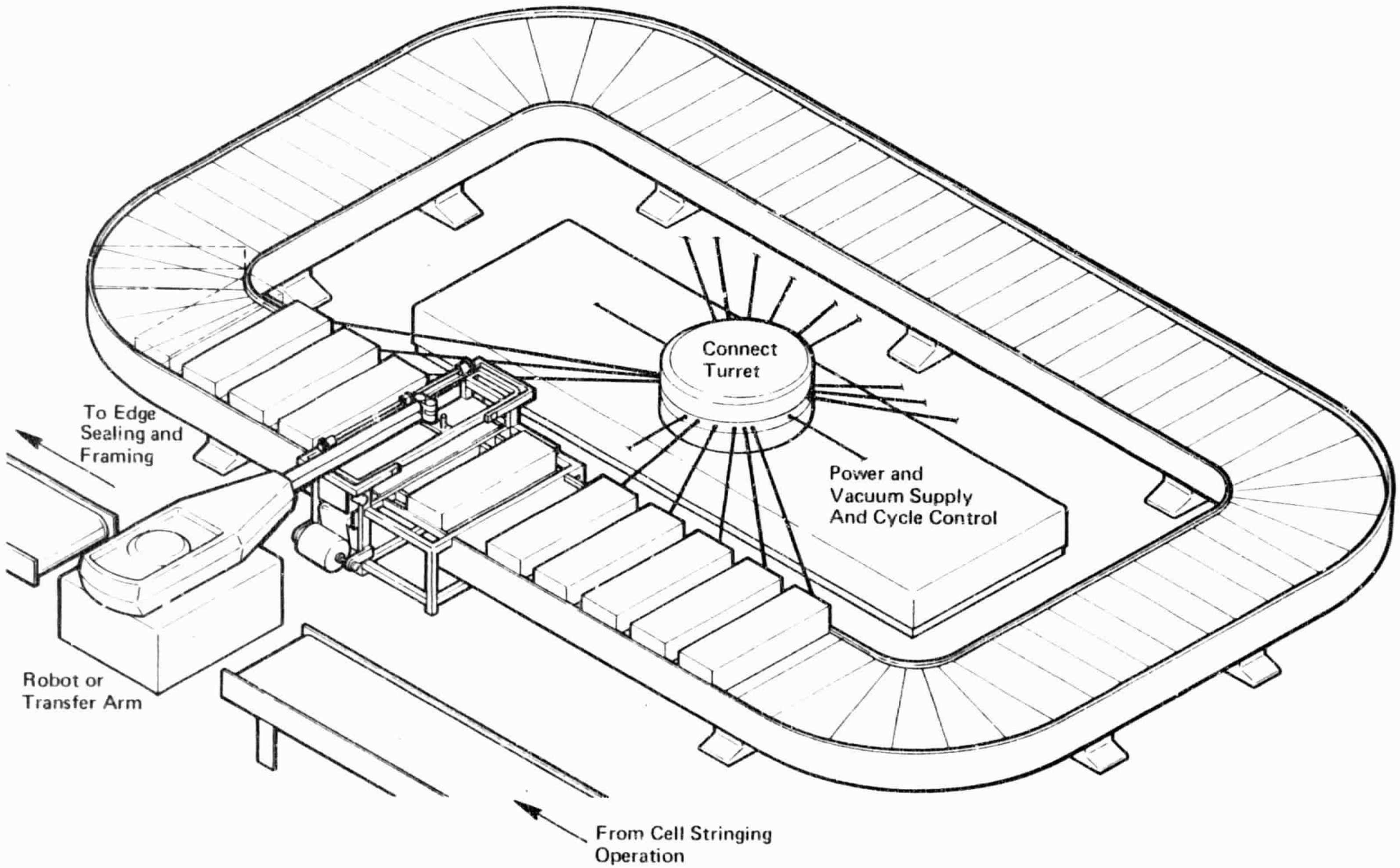


FIGURE 5-21
CONTINUOUS CURING CAROUSEL

A major consideration is to minimize the floor space required. If the 1 ft. wide chambers are spaced 1 ft. apart, then 60 chambers require (1+1) x 60 = 120 linear ft. of carousel.

A circular carousel with a mean diameter of 40 ft. would do it but the floor area required would be 1520 $ft^2$ based on an outside diameter of 44 ft.

A straight sided, round ended carousel (such as used for luggage at airports) with 35 ft. long sides spaced 16 ft. apart has sufficient length and occupies only 1014 $ft^2$ based on outside dimensions. This still leaves a 12'x35' space in the center for control equipment.

### 5.4.2 Batch Curing

An alternative to continuous curing is batch curing which can be done by a system similar to that in Figure 5-21. Considerable floor space can be saved with this system, however, as the carousel is replaced by a linear conveyor which runs from the layup station to a pair of batch processing chambers.

Rather than laying up into an individual chamber, the module is built up directly onto the conveyor surface. For a superstrate design, the glass is laid down first and the module built face down from the top down. For a substrate design, the bottom (substrate) layer is placed down first and the module built face up from the bottom up. After the materials have been placed, the conveyor moves them to the batch chambers.

A minimum of two chambers are required, each holding one "cure cycle's worth" (in this case one hour) of output from the layup station. In this way, while one chamber is cycling, the other is being unloaded/reloaded. As presently conceived, these chambers would have a large number of racks, such as with large commercial ovens. Each module position would have a diaphragm above it to supply the pressure required for lamination.

## 6.0 PHASE FOUR: EDGE SEAL AND FINAL ASSEMBLY

The goal of this phase is to take the encapsulated modules, such as would be removed from the lamination chamber at the end of its

cycle, and turn them into field-installable solar panels.

This requires, at the minimum, edge sealing, framing, and the attachment of (or installment into) a field support structure.

Our approach was to use MBA's Glass Reinforced Concrete (GRC) as a combination substrate, edge frame and support structure. A 4'x8' GRC panel design was developed by MBA for JPL under contract #955281 which was the basis for the panel used for the deliverables on this contract.

The GRC panel has a 1/4" deep indentation on the surface which acts as an edge frame and allows the module's glass surface to be flush with the panel's concrete edge.

The edge seal (a hot melt Butyl) must be applied by a machine that has controlled rectilinear motion.

Figure 6-1 is the original concept sketch of the machine necessary to meet these requirements. The hot melt applicator is held in a fixture that allows it to be moved over the GRC panel in both the X and Y axes independently.

One of the details discussed when setting up the requirements for the deliverables was whether the GRC panel would be large and accommodate several modules such as shown in the figure, or be able to accommodate only one module each. This latter form would be for feasibility demonstration only since such a configuration would have very poor array packing densities.

It was decided that the machine should have the capacity to do a 4'x8' (which is becoming an industry standard) but that the actual deliverables would probably be smaller for ease of portability.

## 6.1 Sequence of Operations

The general sequence of operations for the edge seal machine (processing eight 1'x4' modules per GRC panel) is:

1) The edge sealant is applied along the three sides of the GRC panel where the edges of module #1 will make contact.

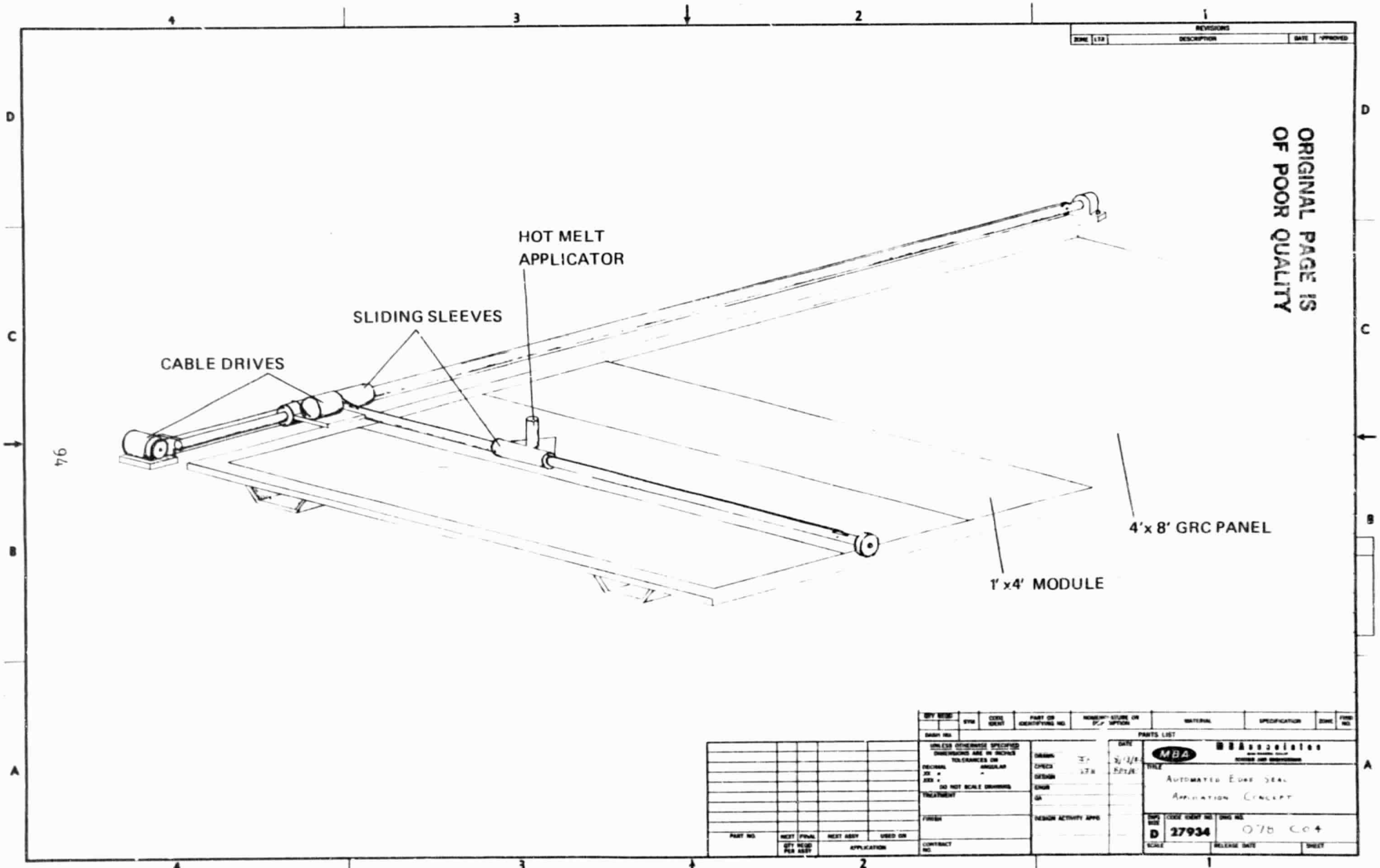


FIGURE 6-1
AUTOMATED EDGE SEAL APPLICATION CONCEPT

2) Module #1 is placed into the GRC panel by the robot.

3) Edge sealant is applied to the panel where the two short sides of module #2 will make contact and along the fourth side of module #1 where the two modules join.

4) Module #2 is placed into the GRC panel by the robot.

5) Steps 3 and 4 are repeated five times for modules 3 thru 7.

6) Edge sealant is applied to all four sides of the remaining opening in the GRC panel.

7) Module #8 is placed into the GRC panel by the robot.

8) The panel is removed for attachment of electrical hardware followed by packing and shipping to the installation site.

9) A new (empty) GRC panel is put in place and the cycle starts over.

The cycle time of the Edge Seal machine would be tied to that of the encapsulation station, i.e., approximately one minute per module or eight minutes for a 4'x8' panel.

It should be noted that while a 4'x8' panel is the maximum size that the machine can process, there is no limit to either the minimum size or graduation of the sizes. Being driven by stepper motors controlled by an interactive computer, the machine can handle any size or shape panel within the resolution of the steppers. Of course, rectangular panels are better suited as the control system's digital nature may become apparent if it tries to follow odd angles or compound curves.

## 6.2 Hardware Development

This station had a relatively short development period as a large number of standardized components could be used.

The machine is composed of three components: shuttle, carriage, and frame. An explanation and description of these components follows. Figure 6-2 is a general view of the completed machine with a 2'x4' GRC panel in position for processing.

### 6.2.1 Frame

Since the Edge Seal machine was designed to apply a hot melt seal to multiple modules (up to eight 1'x4'), the simplicity of inserting and removing GRC panels had to be considered. A standard industrial roller conveyor was decided upon to roll GRC panels into position and provide the basic frame for the rest of the machine.

The frame is the support on which the carriage travels back and forth. The frame has no moving parts, other than the unpowered conveyor rollers.

### 6.2.2 Carriage

The carriage supports the tracks upon which the shuttle rolls. The carriage itself is mounted on rollers which move along tracks on the frame perpendicular to the shuttle. Figure 6-3 shows the carriage sitting in position on the frame with the shuttle, in turn, on it.

The main purpose of the carriage is to move the shuttle along the Y Axis* on top of the frame. The carriage "crawls" along the frame by using a sprocket and chain arrangement driven at both ends via a drive shaft. It has floating rollers on one end to allow for misalignment of the frame. The chain that both the shuttle and carriage "crawl" on is Berg chain, identical to that described in Section 5.3.1.2.

* X axis refers to the 4' length of the GRC Panel, Y axis is the 8' length.

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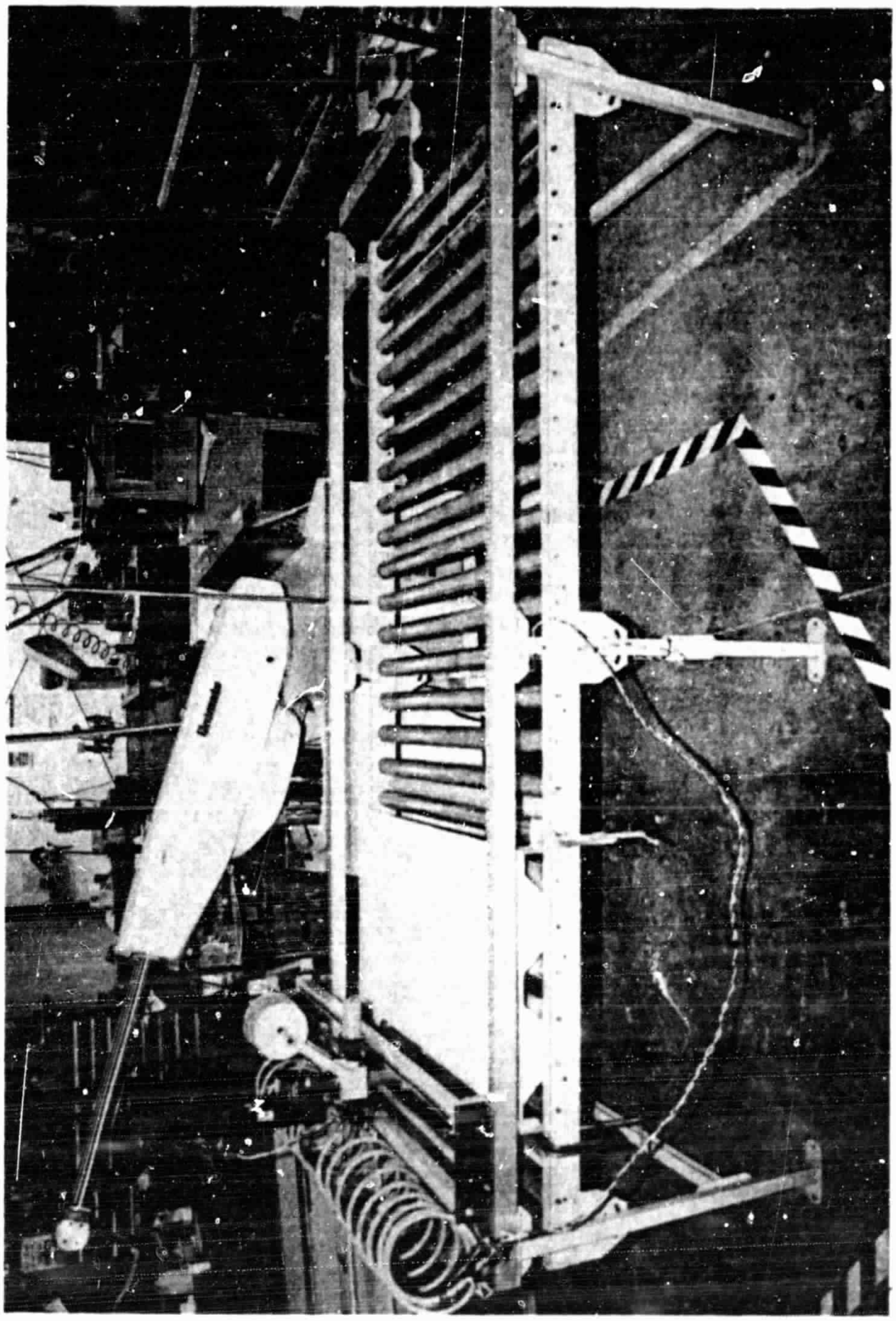

FIGURE 6-2
AUTOMATED EDGE SEALER

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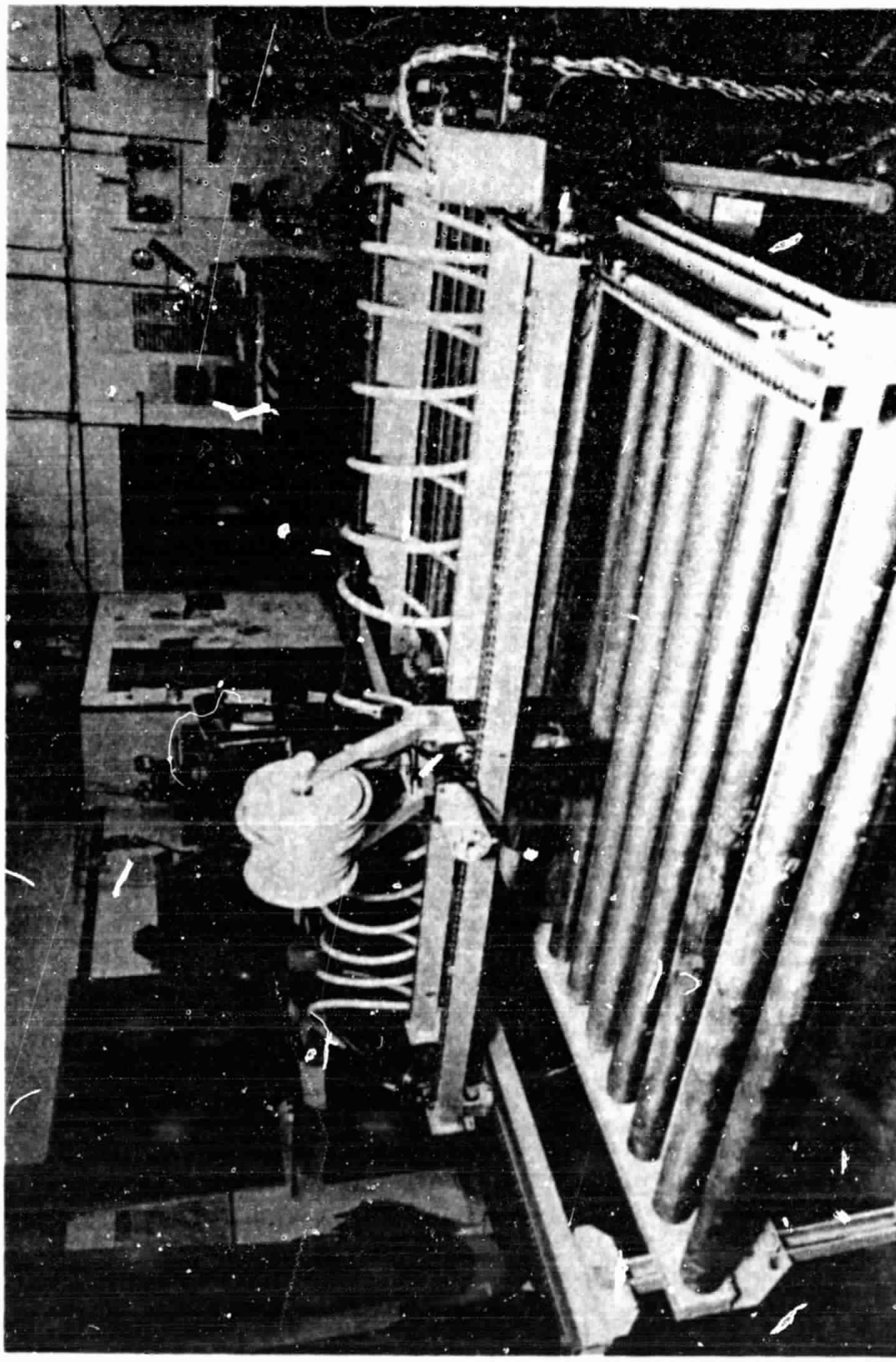

FIGURE 6-3
EDGE SEALER CARRIAGE

### 6.2.3 Shuttle

Figure 6-4 shows the shuttle sitting on top of the carriage. The purpose of the shuttle is to hold the hot melt applicator secure while moving in a controlled linear motion. The shuttle is powered by a horizontally mounted motor, and "crawls" along the X axis by using a sprocket and chain arrangement. To allow for misalignment of the carriage tracks, fixed rollers were used on one side of the shuttle and floating rollers on the opposite side.

### 6.2.4 General

A novel method to control the cables as the shuttle moves across the panel was developed. The two sets of wires (one set for the drive motor and one set for the hot melt gun) are each run through a piece of 1/2" ID coiled air hose. These are then supported on either side of the shuttle in a manner that allows the hose to uncoil as the shuttle travels across the panels (Figure 6-5). When the shuttle returns, the hose, being self storing, simply coils up out of the way.

Tests were run that drive the hot melt gun both in rectangles (i.e. running the X axis and Y axis motors individually) and along diagonals (running both motors simultaneously). To expand on that last point; actually the control system cannot run both motors at the same time. Instead, the software routines that run the motors are set up to operate each motor for only one step (1/200 of a revolution or 0.04" of travel) at a time. These are then placed in a loop to control the number and speed of the steps. The speed of the computer's execution is such that the motion is indistinguishable from true simultaneous operation.

The hot melt gun was tested to determine two important operating parameters: the extrusion rate of the bead and the consumption rate of the Butyl supply rope. The results turned out to be an almost exact 2:1 ratio with the bead extruded at approximately 2 in/sec and the supply rope being consumed at 1 in/sec. The supply spools are approximately 50 ft. each meaning that 100 ft of bead could be extruded from each spool. This is sufficient to edge seal two 4'x8' panels consisting of eight

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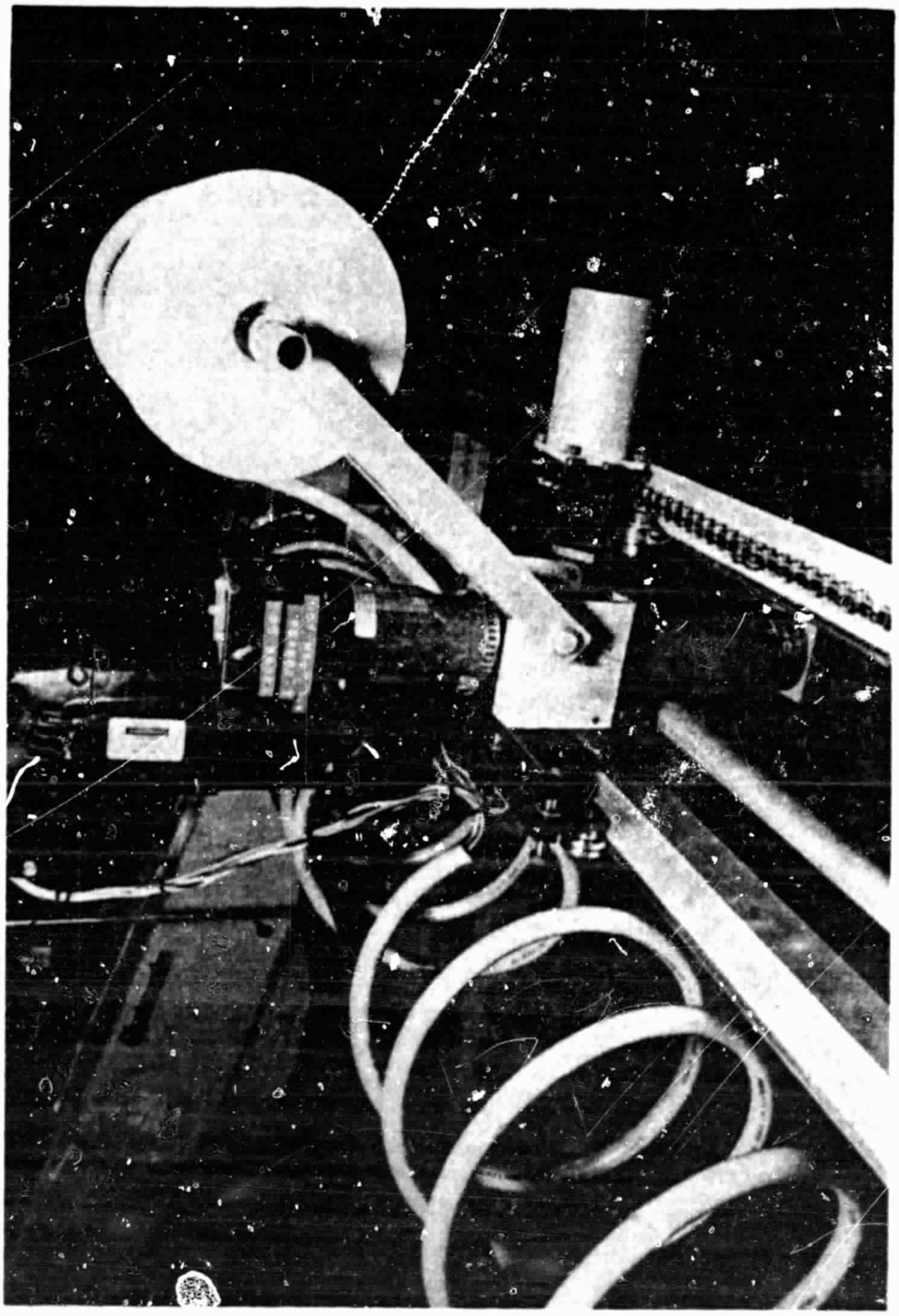

FIGURE 6-4
EDGE SEALER SHUTTLE

Tracor MBA

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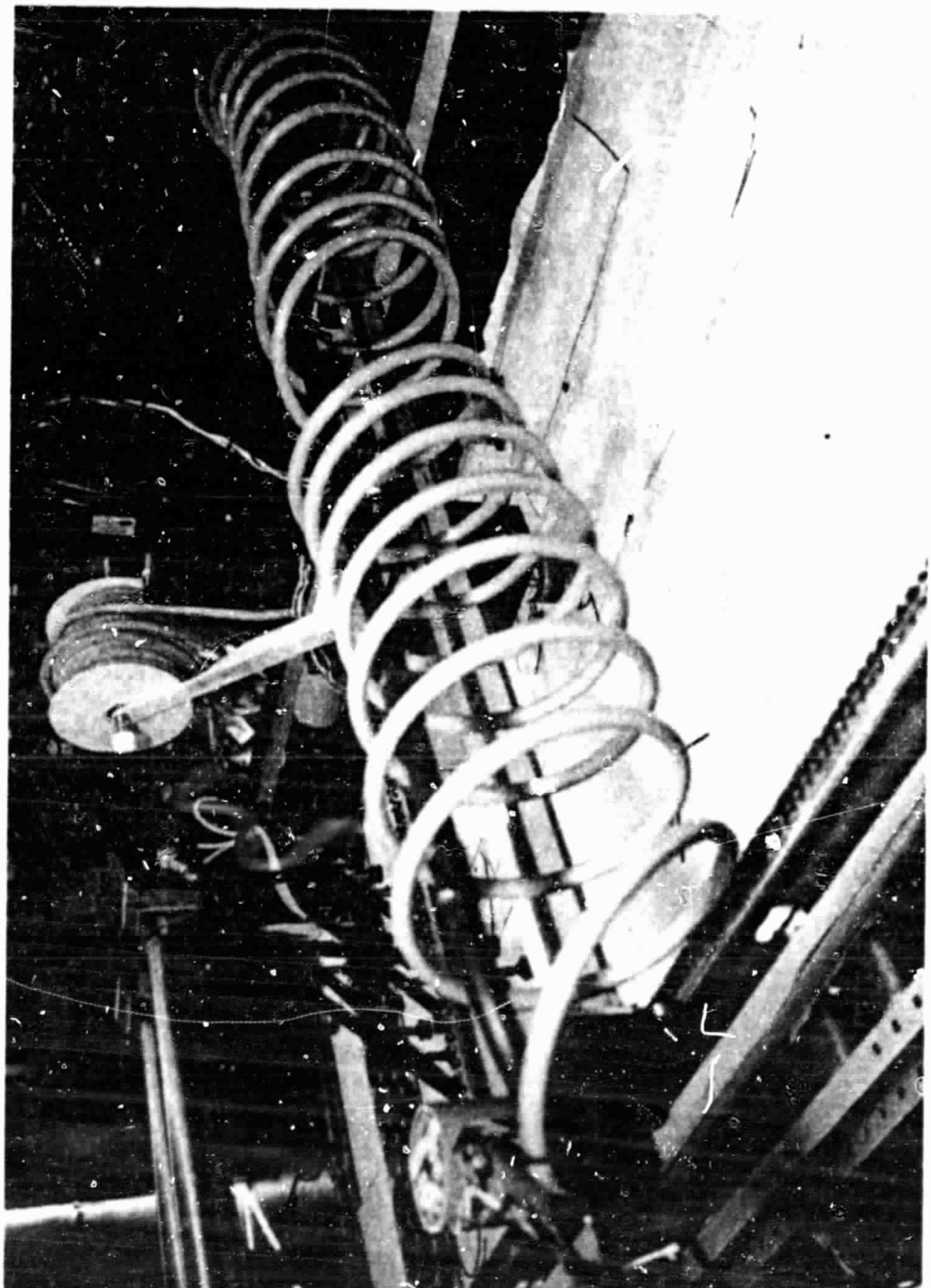

FIGURE 6-5
EDGE SEAL SHUTTLE CABLE CONTROL

Tracor MBA

1'x4' modules each.

## 6.3 Control Electronics

The same set of control electronics is used to control both the Lamination Station and Edge Sealing machine. They are basically the same as those that control the previous cell stringing station but with some important differences. They consist of an interface board which converts the computer's output data into discrete on/off commands, a high current driver board which amplifies these low level commands to operate solenoid valves and stepper motors and finally, an isolator board which is placed between the other two to protect the delicate interface board from any high current surges. The interface board also contains small reed relays to interface with the Unimate robot. All of this equipment uses the same circuit designs as that on the cell preparation station.

Since the control requirements for this equipment are identical for all of the new machines, and since they will never be operated at the same time, as a matter of economy and expediency, we used the same set of electronics for all three new machines (from a control standpoint, the Lamination Chamber is considered a separate machine). Quick disconnectors were used so that the cables could be easily switched. In a production situation, of course, each machine would have its own controller and even in our case separate computer programs for each of the three machines are required.

There are some additional electronics involved with these three new machines to handle requirements not encountered with the original cell stringing system. First is the ability to handle AC line voltage at high current. On the Lamination Chamber, this is necessary to run the chamber heater.

On the Edge Sealing machine, both the hot melt gun heater and feed motor (not to be confused with the shuttle and carriage drive motors which are DC steppers) run on AC. This requirement is met by high current solid state relays (SSR) which are operated by the existing driver transistors.

The other new requirement pertains to the Lamination Chamber only. The chamber has many analog sensing elements (thermistors and a vacuum transducer as detailed in Section 5.3) whose signals must be converted to digital to be understood by the computer. Rather than hooking up each sensor to its own A to D convertor (which are quite expensive) we are using a multiplexer to scan the sensors on a time sharing basis. The multiplexer we are using (a Motorola 14051) can handle up to 8 inputs at one time and output them to a single A to D convertor in a controlled fashion.

Control routines were written for each individual function on the new machines, e.g., shuttle drive, shear solenoid, etc. Each function could then be operated from the computer keyboard simply by giving the RUN command for the appropriate routine. The generalized controlling program was then created by placing all of the individual function routines in the correct order separated by timing waits. The duration of these waits is determined empirically making this (naturally) a repetitive and time consuming process.

## 7.0 PHASE FIVE: FABRICATION

This phase is fairly self explanatory. It requires the fabrication of six $4ft^2$ modules ready to be installed in the field. The cells are to be laid up and interconnected using the equipment developed during the previous contract (and improved during this one). The inter-connected cells are to be encapsulated, edge sealed and framed using equipment developed during this contract.

### 7.1 Deliverable Specifications

It was decided early in the program that the module size would be 1'x4' and that the composition would be the Spectrolab laminate as described in Section 5.2 and illustrated in Figure 5-4. The cell circuit would be patterned after an older ARCO design with 35 series connected cells in three rows of twelve-eleven-twelve. There is an output connector at each end; i.e., no bus bars, just end tabs.

In order to demonstrate the multiple-size capability of the

Final Assembly Station, these six modules have to be laid up on at least two different size GRC substrates. The final size of the substrates was not decided upon until fairly late in the program. For ease of portability during JPL testing it was decided to keep the overall size small. The final deliverable panels are a combination of 1'x4' (one module per panel) and 2'x4' (2 modules per panel) substrates. Figures 7-1 and 7-2 are design sketches of the 1'x4' and 2'x4' GRC panels respectively.

As mentioned in the previous section, these panels are based on a 4'x8' panel developed under a previous contract. Since time and budget constraints did not allow a full stress analysis of the design, it was decided to err on the conservative side and retain the full sized trapazoidal stiffening beam on both panels (one on the 1'x4' and two on the 2'x4') rather than scaling it down. As this beam was designed to provide adequate stiffness to the much larger 4'x8' panel, these small panels are somewhat over designed for strength. Another small change from the 4'x8' design is that the new panels have a 1" wide raised lip around their perimeter which acts as an edge frame whereas the larger panel was flat.

The actual fabrication of these panels was sub-contracted to a local firm that that has GRC spraying equipment and specializes in prototype runs. This provided a considerable savings to the program as the major cost of any short run GRC fabrication involves the setup and breakdown (and in our case refurbishment) of the spraying equipment. Since this vendor is already set up for short runs, we paid only for the materials and labor involved with the actual spraying of the panels. The molds used in the fabrication were built and checked by MBA before being shipped to the vendor.

The extra strength inherent in this design allowed us to take advantage of another advance. Despite all of its advantages, the big drawback to GRC panels, compared to more conventional array structures, is weight. This vendor has perfected a series of lightweight GRC materials that trade off weight for strength. They range from the immensely strong, but very heavy, standard GRC, usable as a structural material, to a very light, air filled version suitable only for decorative castings such as artificial brick. Our panels were made from a middle weight material that replaces the sand

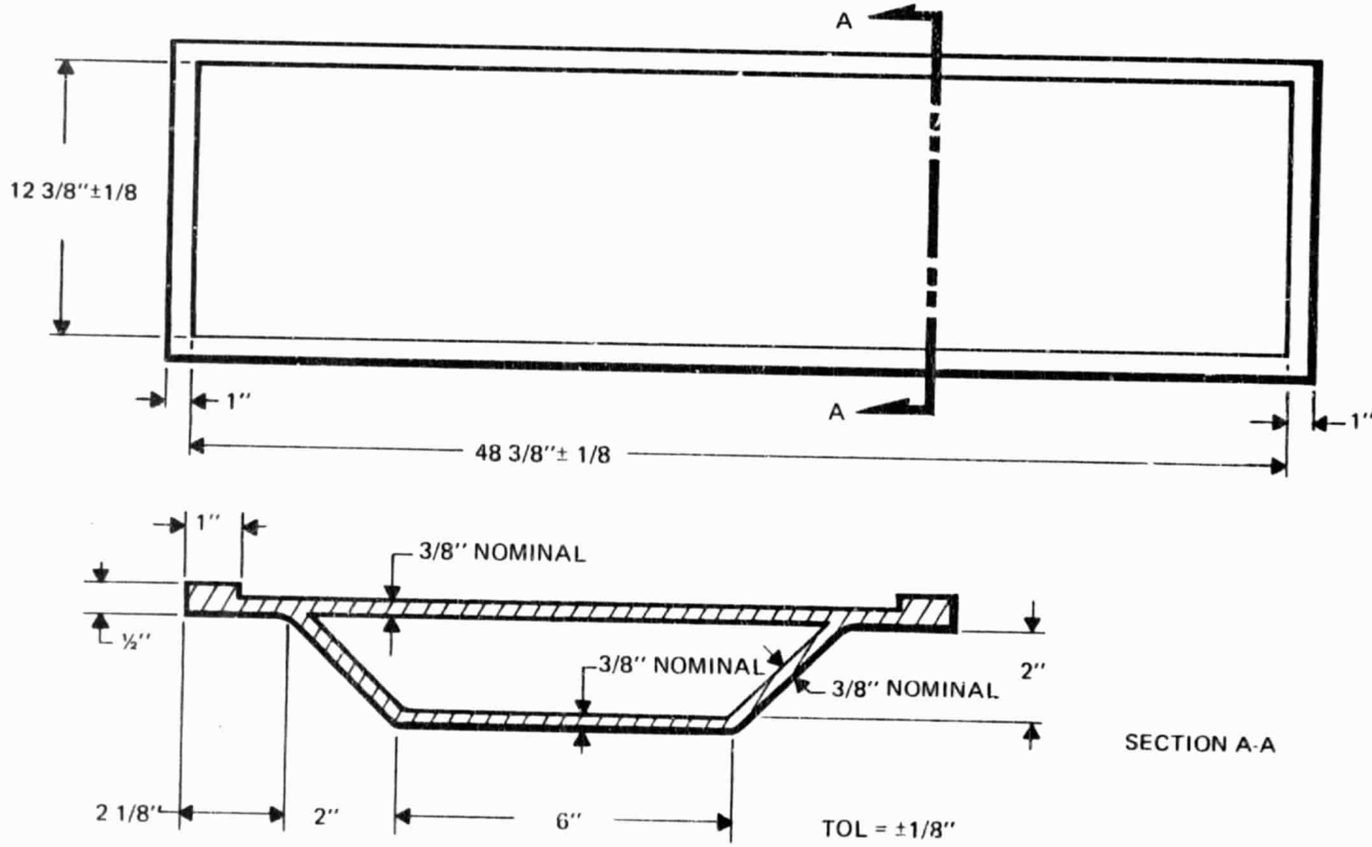


FIGURE 7-1
DESIGN OF 1X4 GRC SUBSTRATE

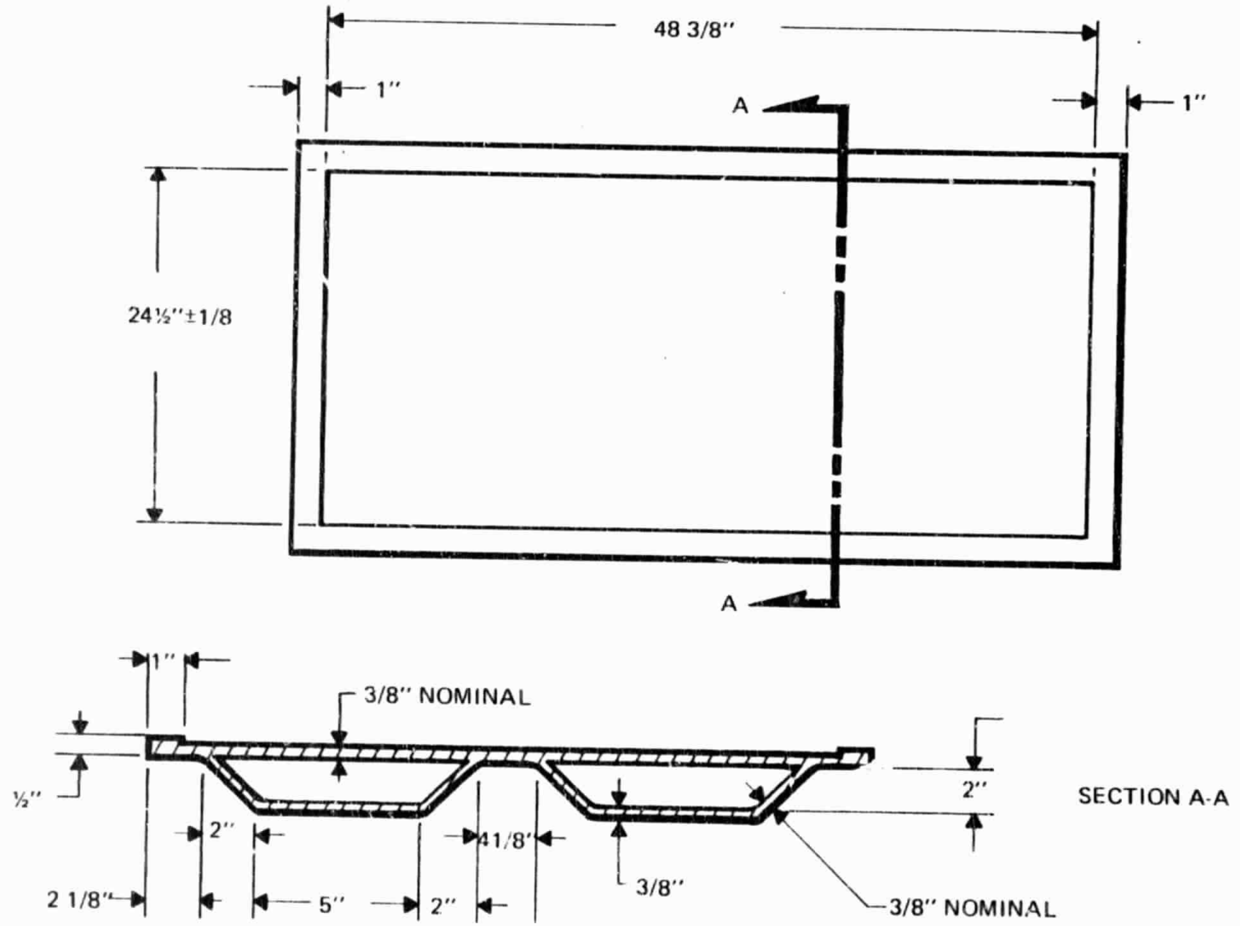


FIGURE 7-2
DESIGN OF 2X4 GRC SUBSTRATE

with diatomaceous earth. The strength is still more than adequate while at the same time realizing a considerable weight savings.

## 7.2 Deliverable Fabrication

The fabrication of the deliverable modules was divided, naturally enough, into cell stringing, laminate layup and curing, and edge sealing. Performance in each of these areas is discussed.

### 7.2.1 Cell Stringing

Modifications to the cell stringing system were completed, as contractually obliged, by 31 December 1980. The system was operating quite well and was, in fact, used two months later to make a demonstration videotape for the 17th PIM in February 1981. At that point, the system was left idle while work concentrated on the development of the Automated Lamination Station and Final Assembly Station.

When the system was re-activated for fabrication of deliverables in early August, it was found to be in very good condition overall. The cell feed, cell orient; ribbon feed, crimp and cut mechanisms; robot pick and place, heat and interface, were all working properly (which means, by implication, that the entire control network was functioning as well).

The solder paste dispensing manifold, however, had deteriorated significantly. The paste in it had solidified rock hard and even after repeated cleaning and reaming, the nozzles could not be made to operate satisfactorily. The paste pattern dispensed was spotty and uneven at best and was a tremendous mess at worst! In the interest of expediency in building these strings, it was decided that the solder paste would be applied by hand. A solution to this problem is presented in "Recommendations", Section 8.1.2.

There was another development, this one beyond our control, that also prevented a fully automated cell stringing. Our system requires that the entire backside of the cell be available as a contact surface. In our system, a certain amount of convergence, divergence or even a slight offset of the leads is inevitible.

The cells used in the deliverables are the current production cell from ARCO Solar. The decision to use these cells was based on ARCO having supplied us with materials in the past and, consequently, our machine being designed around the ARCO metalization pattern. Unfortunately, in their effort to improve performance and lower costs, ARCO has produced a cell that is no longer completely compatible with our machine. The back contact of this cell is mostly a non-solderable aluminum surface. Actual electrical contact is achieved by a dual row of silver pads in a pattern identical to that on the front side. This means that the back side ribbon alignment is just as critical as the front side. As our machine has no provisions to do this operation, it had to be done by hand also.

### 7.2.2 Laminate Layup

All of the components of the Lamination Layup machine were tested individually during construction. True operational testing could not begin, however, until we had the actual materials. Once all lamination materials were in house, the multi-ply supply spools could be wound using our multi-ply roller described in Section 5.2.2.5. Due to the loose wrapping of this hand operated device, there were only about 150 ft. on a 12" diameter spool. Commercial rewinders, with tighter web tension control, could achieve two or three times that amount for the same diameter.

The results of the operational tests were quite encouraging with most of the mechanisms working correctly with little or no adjustments. An early concern was alleviated when the feed rollers were able to easily feed the encapsulant materials into the shuttle. It was feared that either the motor torque and/or the roller friction against the encapsulant would be insufficient to overcome the brake force. Happily, this was not the case although the very fragile Craneglas web did tear while starting during several tests showing that the brake's holding force was still slightly too high. Lowering the brake preload solved this problem. The shuttle, too, had more than adequate torque for pulling the web against the control brake. However, it appeared at first as if the shuttle's clamp would need some modification. Although the material fed smoothly into the clamp, the

clamping force was too low to prevent the material from pulling out of the clamp while it was being drawn out against the brake. The problem turned out to be self correcting when we lowered the brake force as mentioned above. The shuttle now pulls the material smoothly and evenly in both directions.

Laying up of the actual deliverable panels presented surprisingly few problems. The materials were measured, cut, and laid into the chamber with good consistency. An adjustment of the material's position was needed only if the chamber was not placed firmly against its locator stops.

On a somewhat surprising note, the top lamina did not seem to disturb the positions of the cells in the string as it was dragged over them for final positioning. Our suspicion is that the Crangelas layer under the EVA provides a smooth, low, friction surface to slide over the cells.

7.2.3 Encapsulation

The automated encapsulation chamber had some interesting teething problems other than those of the cover previously discussed. The original strip-type ribbon heater burned out spectacularly several times before being replaced with the custom made heater blanket now used. The poly flow (plastic) tubing going to the vacuum transducer melted every cycle while the main vacuum line located less than an inch away (same material) remained intact. The transducer line was replaced with copper pipe.

Once these minor problems were solved, however, the chamber performed with monotonous regularity. Figure 7-3 is the cure cycle used in the controlling computer program. It is based on a combination of both the Springborn and Spectrolab cure cycles, plus the results of our own experiences. The complete specification is included as Appendix D.

Test modules were made using cell fragments or "dead" strings to experiment with some of the parameters. Pre-heating the chamber to 150°F before pumpdown was tried in an effort to eliminate cell cracking

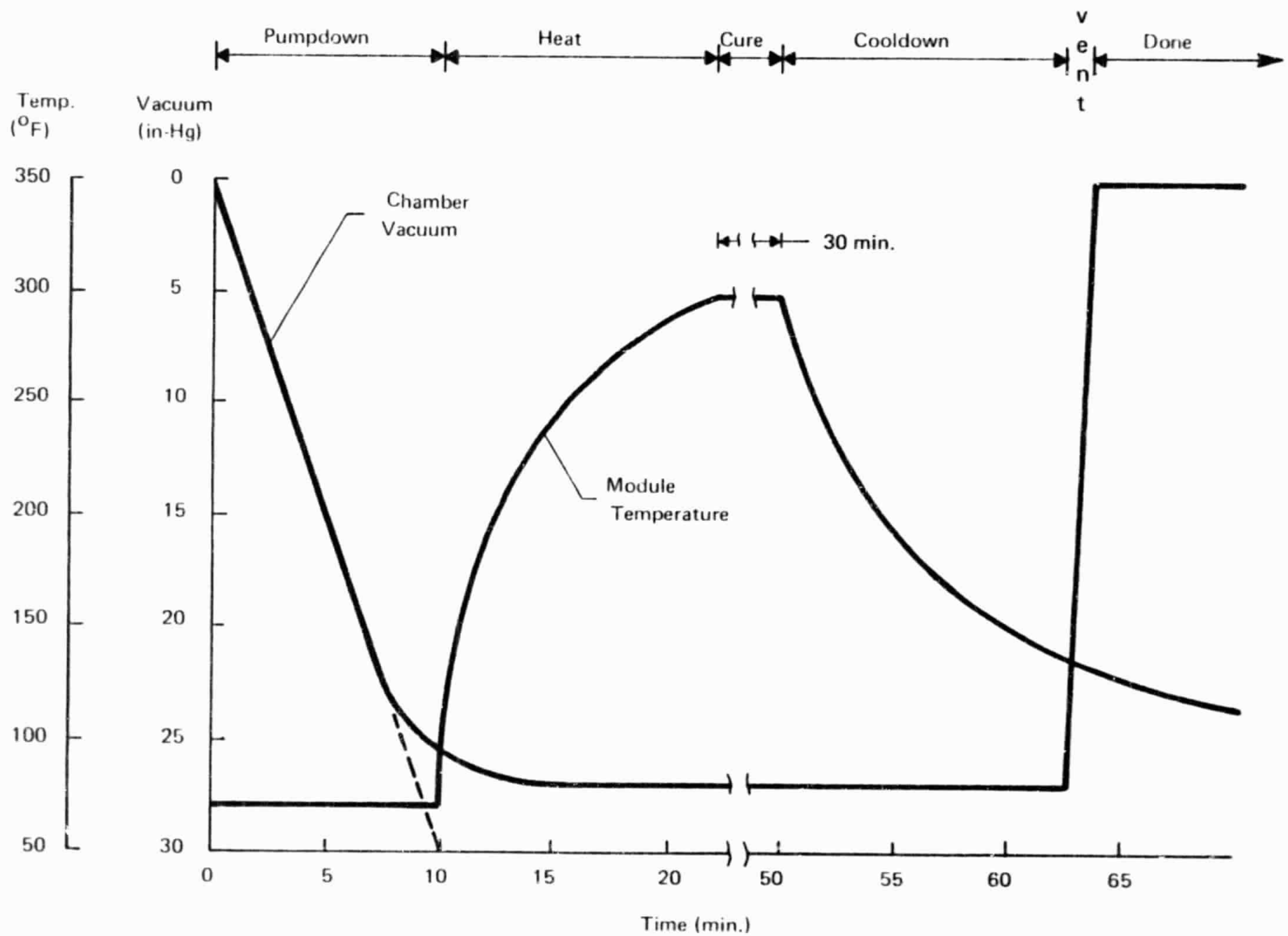


FIGURE 7-3
LAMINATE CURE CYCLE

by softening the EVA, thus giving the cells freedom to displace slightly during pumpdown. This technique did seem to eliminate cracking but the softened EVA tended to "seal off" areas of the module resulting in massive bubbles each covering as much as a two to three cell area.

A total of five test modules, plus eight production modules, were made with the best six being delivered to JPL. As is common with R&D programs, however, experiments continued well into the making of the "production" modules. In one notable occurrence, a production module was being made after normal working hours. A maintenance man, on his normal rounds, unknowingly shut off power to the (temporarily) unattended system less than halfway into the 30 min. high temperature cure phase. The vacuum leaked quickly to ambient and by the time the mishap was discovered, and the system re-initialized, the temperature had dropped over $100^{\circ}F$. The vacuum was restored immediately (rather than the programmed 10 min. pumpdown), the temperature brought back up to $300^{\circ}F$ and the cycle re-started from the middle of the cure phase. Despite this rather unorthodox cycling, the module turned out to be the best produced up to that time!

The point of the above is that EVA and the Spectrolab laminate composition seem to be quite tolerant of cycle variations as long as the minimum requirements for temperature and vacuum as established by Springborn Labs are met.

7.2.4 Edge Seal

There were two problems in making the edge sealer operational, both of them minor. The first was in synchronizing the X-Y positioning motors to the sealant extrusion. Once the tip of the hot melt gun is in position, the extrusion motor is started and the positioning motors begin to move it around the panel. The problem is that there is a delay between the time the extrusion motor starts and the bead of hot melt "lands" on the GRC panel (which is when the positioning motors can start). Conversely, at the other end of the bead, there is a delay (usually not the same) between the time the extrusion motor is shut off and when the bead "breaks free" of the tip. These delays must be determined empirically so that the bead

is uniform and free from "lumps" and "gaps".

The second problem has to do with bead quality. The hot melt gun works by forcing the supply rope down through a heater tube with an auger drive. While being transported through the tube, the temperature of the sealant is raised past its melting point after which it is extruded out the tip. When the extrusion drive is not running, there is enough sealant "in residence" in the heater tube for approximately 1½ ft. of bead. This sealant is all at a very uniform temperature, hence the first foot or so of bead is likewise very uniform. However, the sealant that merely "passes through" the heater tube, that is nearly the entire bead, is not as uniformly heated and the extrusion pulses slightly reflecting the viscosity change with temperature of the sealant. The result is a bead of material with a varying diameter giving it a "curly" look. Since all of the sealant in the bead has been melted, its performance is not impaired, hence any problem is mostly aesthetic.

## 8.0 SUMMARY AND RECOMMENDATIONS

In the two years of this program (counting the hardware development phase of the previous contract), we have more than adequately proven the feasibility of robotic or soft automation in the manufacture of photovoltaic solar panels. The following discussion is a summary of each of the assembly areas, and suggested solutions to observed problems.

### 8.1 Cell Stringing

Being the earliest piece of our system to be designed, the cell stringer has shown the greatest effect from the advancing state-of-the-art. All three areas in which we had problems; back contact lead alignment, solder paste dispensing and robot speed and accuracy, have had their problems solved (or in the first case, created) by advancements in the field.

#### 8.1.1 Back Contact Alignment

The problems encountered by the ARCO cell evolving away from our system, only underscore the importance of soft automation. Had ours been a hard automation system, a major, or even total redesign, would have been necessary. With this programmable system only minor changes are necessary. It may be as simple as installing full length ribbon guides on the preparation station and registration indents on the robot's end effector.

#### 8.1.2 Solder Paste Dispensing

There is something of an art to dispensing small, precision quantities of solder paste or any other high viscosity material. For this feasibility prototype, it was expedient for us to design our own dispensing manifold which was obviously lacking in development time and other refinements.

In a true production machine, designing your own dispenser would be an unnecessary waste of time and effort as there are many excellent "turnkey" systems available commercially. Tridak (Tridak Div., Indicon Inc., Brookfield, CT) in particular has a custom design service.

The standard Tridak precision dispensing system can be equipped with manifolds capable of uniformly applying filled epoxies, solder pastes and other very high viscosity materials in many different geometric patterns.

A multitude of irregularly placed dots, not all of them located in the same horizontal plane nor all the same size, can be readily accommodated. Uniform dots (20 or more) as small as 0.013" diameter can be placed as close as 0.039" on centers all being deposited via a Tridak control system. Location accuracy of $\pm$0.003" is normal.

8.1.3 Robot Speed and Accuracy

In early 1979, when the FSA program first decided to explore programmable automation with available off-the-shelf hardware, the Unimate 2000 was one of the most highly developed and inexpensive industrial robots on the market. In the past 2½ years, however, the robot industry has advanced as quickly as the photovoltaics industry and the 2000 is no longer the best choice for cell stringing.

Unimation has recently introduced the PUMA series of industrial robots. These are smaller, faster, and more accurate than the 2000 and designed specifically for small parts assembly. Scaled to the size of the human arm (PUMAs come in two sizes: one about 50% larger than a human arm for standard assemblies and the other about 75% human size for tiny precision work like assembling circuit boards), the PUMA has a pick and place speed more than twice that of the 2000 with an accuracy of $\pm$0.004" vs the 2000's $\pm$0.05".

An advanced, production oriented version of the cell stringing system was recently sold to Solarex Corporation for use in their MEPSDU. The system uses two PUMA 500 robots and has a production capacity of one 72 cell module, including bus bars and end tabs, every six minutes.

8.2 Module Layup and Encapsulation

While several other companies (Kulicke & Soffa Ind., ARCO Solar Inc., Spire Corp.) have been investigating automated cell stringing, no one else has yet addressed the problem of automated lamination, making ours the pioneering effort.

As the major effort of this contract, the Layup Station received the most attention during the design phase, hence required the least "fiddling" to make it work correctly after fabrication. There are only two suggested improvements. First, to bring the speed up to the targeted 1 module/min. rate, the shuttle drive motor should be enlarged to double the drive screw speed. Second, a minor point, the control brake should be removed as it appears to be unnecessary. The dancer arm (spring loaded both directions) should be retained to aid in web starting and stopping.

The multi-ply supply spools, originally chosen to simplify the mechanical design, have worked out very well. The Craneglas especially has proven to be a most useful material. Not only is it an evacuation aid (its original purpose) during encapsulation, but it also fuctions as an inherent release sheet for the EVA and a cell position retainer during encapsulant layup.

Gila River Products (6615 W. Boston St., Chandler, AZ), a plastics laminating specialty house which supplied the polyester coated aluminum foil, has agreed to produce these rolls in commercial quantities in any width.

Multi-ply spools also considerably simplify machine operation as well. It is much faster to change and thread a single spool at each end rather than four separate spools at one end and two at the other. Separate spools would most likely be of different lengths meaning that they would run out at different times making necessary frequent stops to reload.

The encapsulating chamber again points out the advantage of digital control. With only a bare minimum of equipment, we were able to turn out modules equal to those of much more mechanically sophisticated laminators because of our interactive control.

Even though the chamber worked quite well for a single chamber vacuum bag, the current trend towards double chambers points out the deficiencies of the single chamber design. The problems of cells and (in two test cases) glass cracking, and the very long and critical pumpdown phase

both are eliminated with the double chamber design. It is, therefore, just as well that the "soft-top" chamber cover had to be discarded in favor of the rigid frame as the soft cover is not applicable to the double chamber design.

### 8.3 Edge Seal

Automated edge sealing is another area of panel manufacture which the industry in general has yet to address. As it is even further "downstream" in the assembly process than module layup, there was less of an industry consensus to use as a basis for our design.

Although the machine proved quite adequately the feasibility of automated edge seal application, it is by far the furthest from a production-ready machine of the three. In fact, in MBA's opinion, a second pre-production prototype is required to prove its adaptability to a true production situation. Suggested changes to be incorporated on a second generation prototype include the following.

#### 8.3.1 Drive System

Due to their digital nature, stepper motors require flexible elements in the driven system to absorb the intermittent or "cogging" motions. In the edge sealer, the Berg chain served as this flexible element. Because of this flexibility, however, there were problems in maintaining consistent height and alignment to keep the drive gears engaged. For this reason a more rigid, stable drive, like rack-and-pinion, should be used with an intermediate toothed rubber drive belt (such as used on the Laminate Layup Machine shuttle and roller drives) to provide the flexible element.

#### 8.3.2 Hot Melt Delivery

For expediency, this program used the existing, JPL supplied, Hardman PSA hot melt gun as the sealant applicator. Adapting a device designed to be hand operated to automated operation is limited at best. The problems encountered with extrusion/motor synchronization, extrusion speed (the variable-speed "trigger" on the PSA had to be removed for automated operation) and uneven bead temperature and consistency all stem from this.

Many hot melt equipment manufacturers (Nordson, 3M, etc.) make systems specifically designed for automated operation. These systems consist of floor mounted heaters and pumps that deliver the melted sealant to remote located nozzles via heated hoses. This provides for even temperatures and consistencies and allows for constant sealant replenishment without stopping the machine.

### 8.3.3 Versatility

The existing machine is somewhat hampered by requiring the use of GRC panels. While MBA supports the use of this material, there are many photovoltaic applications for which GRC is not suited. A true production machine should be able to apply an edge seal directly to a module with no frame required. Such a machine would be applicable to many different edge frame designs.

## 8.4 Drawing Package

The drawing package has, in a sense, been in production for the entire duration of the contract since all of the machining prints used in the assembly of these machines are included.

Once the machines were completed and operating, however, the assembly drawings could be produced.

A complete set of assembly, sub assembly, machine prints and electrical drawings were delivered to JPL along with the developed hardware and deliverable panels.

APPENDIX A

SAMICS Formats A and B with appendices

# SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

## FORMAT B — COMPANY DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

| Company Referent |
|---|
| ROBOTMOD |

DESCRIPTIVE NAME
Module manufacturing company using industrial robot based assembly equipment

| | | | |
|---|---|---|---|
| 0. | (b) | (Final) Product(s) Produced | PANEL |
| | (a) | (Final) Process(es) | ROBOTSEAL |
| | (c) | Ideal Ratio(s) with units | 0.125 Panels/module |
| 1. | (b) | Intermediate Product(s) | CUREMOD |
| | (a) | Process(es) | CURE |
| | (c) | Ideal Ratio(s) with units | 1.0 modules/module |
| 2. | (b) | Intermediate Product(s) | LAYMOD |
| | (a) | Process(es) | ROBOTLAY |
| | (c) | Ideal Ratio(s) with units | 1.0 modules/string |
| 3. | (b) | Intermediate Product(s) | STRING |
| | (a) | Process(es) | ROBOTBOND |
| | (c) | Ideal Ratio(s) with units | |
| 4. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| 5. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| 6. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| 7. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| 8. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| 9. | (b) | Intermediate Product(s) | |
| | (a) | Process(es) | |
| | (c) | Ideal Ratio(s) with units | |
| | | Purchased Product(s) | |
| | | Supplier and Percentage | |
| | | Supplier and Percentage | |

PREPARED BY John J. Hagerty

DATE 18 June 81

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

# SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS



## FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]

ROBOTBOND

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process Placement and soldering of cell string using an industrial robot

### PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent] STRING

A-4 Descriptive Name [Product. Name] Interconnected String of Cells

A-5 Unit Of Measure [Product. Units] STRINGS

### PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput) 0.1622 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time] 6.1667 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle] 0.97 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day] 3 Shifts

A-8b [Personnel. Integerization. Override. Switch] off (Off or On)

### PART 3 – EQUIPMENT COST FACTORS (Machine Description)

| | | | |
|---|---|---|---|
| A-9 Component [Referent] | ROBOT | CELLPREP | I-HEATER |
| A-9a Component [Descriptive. Name] | Unimate 2000B Robot | Cell Preparation Station | Induction Heater Generator |
| A-10 Base Year For Equipment Prices [Price. Year] | 1979 | 1979 | 1981 |
| A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component) | 49,685 | 56,500 | 8,000 |
| A-12 Anticipated [Useful. Life] (Years) | 4.83 | 7 | 10 |
| A-13 [Salvage. Value] ($ Per Component) | 24,842 | 2825 | 400 |
| A-14 [Removal. And. Installation. Cost] ($/Component) | 700 | 500 | 200 |

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 *), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

A-15 Process Referent (From Front Side Line A-1) ROBOTBOND

**PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)**

[Facility. Or. Personnel Requirement]

| A-16 Catalog Number (Expense Item Referent) | A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine] | A-19 Units | A-17 Requirement Description or Name |
|---|---|---|---|
| A2064D | 125 | $ft^2$ | Type A Manufacturing Space |
| B3752D | 0.25 | Person/shift | Production machine operator |
| B3736D | 0.0179 | Person/shift | Mechanical maintenance |
| B3688D | 0.0089 | Person/shift | Electrical maintenance |

**PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE** (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

| A-20 Catalog Number (Expense Item Referent) | A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle] | A-23 Units | A-21 Requirement Description or Name |
|---|---|---|---|
| E1140D | 0.0446 | $m^2$ | Solar cells |
| EA3D | 0.0063 | lb | Copper ribbon |
| EG1600D | 0.0031 | lb | Solder paste |
| C1032B | 0.3083 | KW-Hr | Electricity |
| C2032D | 18.55 | $ft^3$ | Compressed air |

**PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED** None

| A-24 [Required. Product] (Reference) | A-28 [Yield] * (%) | A-26 [Ideal. Ratio] ** Of Units Out/Units In | A-27 Units Of A-26*** | A-25 Product Name |
|---|---|---|---|---|
| | | | | |

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DATE 18 June 81

*100% minus percentage of required product lost in this process.
**Assume 100% yield here.
***Examples: Modules/Cell or Cells/Wafer.

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# SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

## FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]
ROBOTLAY

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process: Layup of Encapsulant Materials using an Industrial Robot

**PART 1 – PRODUCT DESCRIPTION**

A-3 [Product. Referent]: LAYMOD

A-4 Descriptive Name [Product. Name]: Laid-up module ready for curing

A-5 Unit Of Measure [Product. Units]: Modules

**PART 2 – PROCESS CHARACTERISTICS**

A-6 [Output. Rate] (Not Thruput): 1.0 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time]: 1.0 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle]: 0.956 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day]: 3 Shifts

A-8b [Personnel. Integerization. Override. Switch]: off (Off or On)

**PART 3 – EQUIPMENT COST FACTORS** (Machine Description)

| | | | |
|---|---|---|---|
| A-9 Component [Referent] | ROBOT* | LAM-PREP | |
| A-9a Component [Descriptive. Name] | Unimate 2000B Robot | Lamination Preparation Station | |
| A-10 Base Year For Equipment Prices [Price. Year] | 1979 | 1981 | |
| A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component) | 33,105 | 110,000 | |
| A-12 Anticipated [Useful. Life] (Years) | 4.83 | 10 | |
| A-13 [Salvage. Value] ($ Per Component) | 16,553 | 6,000 | |
| A-14 [Removal. And. Installation. Cost] ($/Component) | 467 | 800 | |

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 *), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

*The robot is used as both an assembly and transfer device between this station and the edge seal station (pages 7 & 8). Its time is split 2/3 here and 1/3 there. The values on A-11, A-13 and A-14 on both forms are pro-rated by that proportion. The same applies to maintenance and direct machine requirements.

A-15 Process Referent (From Front Side Line A-1) ROBOTLAY

**PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)**

[Facility. Or. Personnel Requirement]

| A-16 Catalog Number (Expense Item Referent) | A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine] | A-19 Units | A-17 Requirement Description or Name |
|---|---|---|---|
| A2064D | 150 | $ft^2$ | Type A manufacturing space |
| B3752D | 0.5 | person/shift | Production machine operator |
| B3736D | 0.0119+ | person/shift | Mechanical maintenance |
| B3688D | 0.0060+ | person/shift | Electrical maintenance |

**PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE** (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

| A-20 Catalog Number (Expense Item Referent) | A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle] | A-23 Units | A-21 Requirement Description or Name |
|---|---|---|---|
| E1828D | 4 | $ft^2$ | Float glass (tempered) |
| E1807D | 12 | $ft^2$ | Crane glass |
| EPI003 | 8 | $ft^2$ | 1 sheet clear EVA |
| | | | 1 sheet white EVA |
| EMBA01 | 4 | $ft^2$ | Polyester/foil laminate |
| C1032B | 0.136 | KW-Hr | Electricity |
| C2032D | 2.458 | $ft^3$ | Compressed air |

**PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED**

| A-24 [Required. Product] (Reference) | A-28 [Yield] * (%) | A-26 [Ideal. Ratio] ** Of Units Out/Units In | A-27 Units Of A-26*** | A-25 Product Name |
|---|---|---|---|---|
| STRING | 97 | 1 | Modules/string | Interconnected string of cells |

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DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

+ See note at bottom of page 3

# SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

## FORMAT A — PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr / Pasadena, Calif 91103

A-1 Process [Referent]
CURE

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process Evacuate and thermal cycle module for curing

**PART 1 – PRODUCT DESCRIPTION**

A-3 [Product. Referent] CUREMOD

A-4 Descriptive Name [Product. Name] Encapsulated module ready for edge sealing and framing

A-5 Unit Of Measure [Product. Units] modules

**PART 2 – PROCESS CHARACTERISTICS**

A-6 [Output. Rate] (Not Thruput) 1.0 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time] 60 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle] 0.98 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day] 3 Shifts

A-8b [Personnel. Integerization. Override. Switch] off (Off or On)

**PART 3 – EQUIPMENT COST FACTORS** (Machine Description)

| | | | |
|---|---|---|---|
| A-9 Component [Referent] | CAROUSEL | | |
| A-9a Component [Descriptive. Name] | Auto-cycling thermal/vacuum multi-chamber | | |
| A-10 Base Year For Equipment Prices [Price. Year] | 1981 | | |
| A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component) | $85,000 | | |
| A-12 Anticipated [Useful. Life] (Years) | 20 | | |
| A-13 [Salvage. Value] ($ Per Component) | 4,250 | | |
| A-14 [Removal. And. Installation. Cost] ($/Component) | 5,000 | | |

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 *), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

Format A: Process Description (Continued)



A-15 Process Referent (From Front Side Line A-1) CURE

**PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)**

[Facility. Or. Personnel Requirement]

| A-16 Catalog Number (Expense Item Referent) | A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine] | A-19 Units | A-17 Requirement Description or Name |
|---|---|---|---|
| A 2064D | 1014 | $ft^2$ | Type A manufacturing space |
| B 3752D | 0.5 | person/shift | Production machine operator |
| B 3736D | 0.0064 | person/shift | Mechanical maintenance |
| B 3688D | 0.0139 | person/shift | Electrical maintenance |

**PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE** (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

| A-20 Catalog Number (Expense Item Referent) | A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle] | A-23 Units | A-21 Requirement Description or Name |
|---|---|---|---|
| C 1032B | 1.1103 | KWH | Electricity |

**PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED**

| A-24 [Required. Product] (Reference) | A-28 [Yield] * (%) | A-26 [Ideal. Ratio] ** Of Units Out/Units In | A-27 Units Of A-26*** | A-25 Product Name |
|---|---|---|---|---|
| LAYMOD | 99 | 1 | Modules/Module | Laid-up modules |

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DATE 18 June 81

*100% minus percentage of required product lost in this process.

**Assume 100% yield here.

***Examples: Modules/Cell or Cells/Wafer.

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# SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

## FORMAT A — PROCESS DESCRIPTION

A-1 Process [Referent]: ROBOTSEAL

Note: Names given in brackets [ ] are the names of process attributes requested by the SAMIS computer program.

A-2 [Descriptive. Name] of Process: Apply edge seal and frame using an industrial robot

### PART 1 – PRODUCT DESCRIPTION

A-3 [Product. Referent]: PANEL

A-4 Descriptive Name [Product. Name]: Completed panel, ready for packing and shipping

A-5 Unit Of Measure [Product. Units]: Panels

### PART 2 – PROCESS CHARACTERISTICS

A-6 [Output. Rate] (Not Thruput): 0.125 Units (given on line A-5) Per Operating Minute

A-7 [Inprocess. Inventory. Time]: 8.0 Calendar Minutes (Used only to compute in-process inventory)

A-8 [Duty. Cycle]: 0.97 Operating Minutes Per Minute

A-8a [Number. Of. Shifts. Per. Day]: 3 Shifts

A-8b [Personnel. Integerization. Override. Switch]: off (Off or On)

### PART 3 – EQUIPMENT COST FACTORS (Machine Description)

| | | | |
|---|---|---|---|
| A-9 Component [Referent] | ROBOT* | SEAL-STN | |
| A-9a Component [Descriptive. Name] | Unimate 2000B Robot | Edge Seal and Framing Station | |
| A-10 Base Year For Equipment Prices [Price. Year] | 1979 | 1981 | |
| A-11 [Purchase. Cost. Vs. Quantity. Bought. Table] (Number Of and $ Per Component) | 16,562 | 50,000 | |
| A-12 Anticipated [Useful. Life] (Years) | 4.83 | 10 | |
| A-13 [Salvage. Value] ($ Per Component) | 8,281 | 2,500 | |
| A-14 [Removal. And. Installation. Cost] ($/Component) | 233 | 500 | |

Note: The SAMIS computer program also prompts for the [Payment. Float. Interval], the [Inflation. Rate. Table], the [Equipment. Tax. Depreciation. Method], and the [Equipment. Book. Depreciation. Method]. In the LSA SAMICS context, use 0.0, (1975 6.0 •), DDB, and SL. (The asterisk is a signal to the computer, not a reference to a footnote.)

*See note at bottom of page 3

A-15 Process Referent (From Front Side Line A-1) ROBOTSEAL

**PART 4 – DIRECT REQUIREMENTS PER MACHINE (Facilities) OR PER MACHINE PER SHIFT (Personnel)**

[Facility. Or. Personnel Requirement]

| A-16 Catalog Number (Expense Item Referent) | A-18 Amount Required Per Machine (Per Shift) [Amount. Per. Machine] | A-19 Units | A-17 Requirement Description or Name |
|---|---|---|---|
| A2064D | 80 | $ft^2$ | Manufacturing space type A |
| B3752D | 1.0 | person/shift | Production machine operator |
| B3736D | 0.0060 | person/shift | Mechanical maintenance |
| B3688D | 0.0029 | person/shift | Electrical maintenance |

**PART 5 – DIRECT REQUIREMENTS PER MACHINE PER MINUTE** (SAMIS will ask first for Byproducts)

[Byproduct] and [Utility. Or. Commodity Requirement]

| A-20 Catalog Number (Expense Item Referent) | A-22 Amount Required Per Machine Per Minute [Amount. Per. Cycle] | A-23 Units | A-21 Requirement Description or Name |
|---|---|---|---|
| EMBA02 | 4.0 | $ft^2$ | GRC Panel |
| EMBA03 | 3.25 | ft | Butyl Rope |
| C1032B | 0.0679 | KWH | Electricity |
| C2032D | 0.3646 | $ft^3$ | Compressed air |

**PART 6 – INTRA-INDUSTRY PRODUCT(S) REQUIRED**

| A-24 [Required. Product] (Reference) | A-28 [Yield]* (%) | A-26 [Ideal. Ratio]** Of Units Out/Units In | A-27 Units Of A-26*** | A-25 Product Name |
|---|---|---|---|---|
| CUREMOD | 100 | 0.125 | Panels/module | Encapsuled Module |

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DATE 18 June 81

*100% minus percentage of required product lost in this process.
**Assume 100% yield here.
***Examples: Module /Cell or Cells/Wafer.

Appendix for Process ROBOTBOND

A-6→A-7 Cycle time 10 sec/cycle → 6 cycles/min

String has 35 cells + 2 end bus bars = 37 cycles

$$\frac{37}{6} = \underline{\underline{6.1667 \text{ min/string}}}$$

$$\rightarrow \underline{\underline{0.1622 \text{ strings/min}}}$$

A-8 Ribbon and solder paste supplies sized to be changed once per shift, a 5 min. job.

$$\frac{5}{480} = 0.0104 \text{ down fraction } 1 - 0.01 = 0.99 \text{ up fraction}$$

Unimate up time 98% (manufacturer's estimate)

$$(0.99)\times(0.98) = 0.97$$

A-9→A-14

Unimate 2000B

Purchase Price: $\underline{\underline{\$\ 49,685.}}$ Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate) → $\underline{\underline{4.83 \text{ yrs.}}}$

Salvage Value: 50% (manufacturer's estimate) before overhaul

→ $\underline{\underline{\$24,842}}$

Installation and Removal Costs: $\underline{\underline{\$700}}$ Based on experience with current robot.

Cell Preparation Station

| | | |
|---|---|---|
| Purchase Price: | $ 50,000 | Construction labor |
| | 2,600 | Siltec Cassette Unloader |
| | 2,300 | Computer & Interface |
| | 1,600 | Enclosure |
| | $ 56,500 | |

Useful Life: $\underline{\underline{7 \text{ years}}}$ (Engineering Estimate)

Salvage Value: 5% (Engineering Estimate) → $\underline{\underline{\$2825}}$

Installation and Removal Costs: $\underline{\underline{\$500}}$ (Estimate)

Appendix for Process ROBOTBOND (Continued)

A-9→A-14

Induction Heater

Purchase Price: $8,000

Useful Life: 10 years (Industrial Estimate)

Salvage Value: 5% (Engineering Estimate) → $400

Installation and Removal Costs: $200

A-16→A-19 Mfg. Space: 125 $ft^2$ (based on current machine)

Machine Operator: One person can watch four systems

Maintenance:

| | | |
|---|---|---|
| Scheduled - 6.5 hr/1000 hr (mfg. est.) | → | 1.092 hr/wk |
| Unscheduled (98% up time) - | | 3.360 |
| | | 4.452 hr/wk |
| | ≈ | 4.5 hr/wk |

Required Maintenance 4.5 hr/wk assume 2/1 ratio mechanical to electrical.

Mechanical: $3.0\ \frac{hr}{wk} \times \frac{1}{21}\ \frac{wk}{shift} \times \frac{1}{8}\ \frac{shift}{man\text{-}hr} = \underline{0.0179}$ person/shift

Electrical: $1.5\ \frac{hr}{wk}$ - - - - - - - - - - - - - - - - - - = $\underline{0.00893}$ person/shift

Appendix for Process ROBOTBOND (Continued)

A-20→A-23

Solar Cells:

100mm = 0.0079 $m^2$/cell

@ 35 cells/string = 0.2749 $m^2$/string

@ 0.1622 strings/min = 0.0446 $m^2$/min

Copper Ribbon:

2 types - interconnect & bus bar

Interconnect ribbon is 0.1" x 0.002"

two 7" ribbons per cell = 14 in/cell

@ 35 cells/string = 490 in/string

490 x 0.100 x 0.002 = 0.0980 $in^3$/string

Bus bar is 0.5" x 0.01"

2 Bus bars per string, 2.25" long

2x2.25 x 0.5 x 0.01 = 0.0225 $in^3$/string

0.0980 + 0.0225 = 0.1205 $in^3$/string

Density of copper = 0.3237 lb/$in^3$

0.1205 x 0.3237 = 0.0390 lb/string

@ 0.1622 strings/min = 0.0063 lb/min

Solder Paste:

Each cell requires 4 solder beads each 3" long

For 0.015" dia. bead: $\left(\frac{.015}{2}\right)^2 \Pi \times 3 \times 4 = 0.0021$ $in^3$/cell

@ 35 cells/string = 0.0742 $in^3$/string (Includes connection to bus bars)

Solder paste density = 0.2575 lb/$in^3$

0.0742 x 0.2575 = 0.191 lb/string

@ 0.1622 string/min = 0.0031 lb/min

Appendix for Process ROBOTBOND (Continued)

A-20→A-23

Electricity:

| | | |
|---|---|---|
| Robot | 12.0 KW | manufacturer specs. |
| Induction Heater | 5.5 KW | |
| Preparation Station | 1.0 KW | Sum of electrical equipment in preparation station |
| | 18.5 KW | |

= 18.5 KWH/hr → 0.3083 KWH/min

Compressed Air:

System contains two model B-100 eductors, each rated @ 20 scfm

1) The prep station eductor runs 5.5 sec of the 10 sec. cycle

$$\rightarrow \frac{5.5}{10} \times 20 = 11.0 \text{ cfm}$$

2) The robot eductor runs an average of 3 sec/cycle

$$\rightarrow \frac{3}{10} \times 20 = 6 \text{ cfm}$$

3) The prep station air table runs 2.5 sec/cycle @ ≃ 1 cfm

$$\rightarrow \frac{2.5}{10} \times 1 = 0.25 \text{ cfm}$$

4) The robot "cell release" air is on 3 sec/cycle @ ≃ 1 cfm

$$\rightarrow \frac{3}{10} \times 1 = 0.30 \text{ cfm}$$

5) 3 small cylinders and 4 solder paste tubes use ≃1 cfm

Total Air:

| | |
|---|---|
| 11.0 | |
| 6.0 | |
| 1.0 | |
| .25 | |
| .30 | |
| 18.55 | $ft^3$/min. |

Appendix for Process ROBOTLAY

A-6→A-7 Machine cycle time = 1 min.

A-8 Bottom Lamina Supply Spool must be changed 4 times per shift (a 2 min. job) : 4x2 = 8 min/shift

Top Lamina Supply Spool must be changed 2 times per shift:

2x2 = 4 min/shift

$$\frac{8\text{x}4 \quad \text{min down}}{480 \quad \text{min total}} = 0.025 \text{ down fraction} \rightarrow 1-0.025 = 0.975 \text{ up fraction}$$

Unimate up fraction = 0.98 (mfg. est.)

0.98 x 0.975 = <u>0.956</u>

A-9→A-14

<u>Robot</u> - Unimate 2000B

Purchase Price: <u>$ 49,685</u> Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate) → <u>4.83 yrs.</u>

Salvage Value: 50% (manufacturer's estimate) before overhaul → <u>$24,842</u>

Installation and Removal Costs: <u>$700</u> Based on experience with current robot.

<u>See note at bottom of page 3</u>

<u>Lamination Station</u>

Purchase Price: Development costs of prototype

Useful Life: 10 yrs (engineering estimate)

Salvage value: 5% of purchase price

Removal & installation cost: 2 man weeks installation

Appendix for Process ROBOTLAY

A-16→A-19

Manufacturing Space: 150 $ft^2$ (based on current machine)

Machine Operator: The operator divides his time between this machine and the curing chambers in process CURE.

Maintenance: Scheduled - 6.5 hr/1000 hr (mfg. est.) → 1.092 hr/wk
Unscheduled (98% up time) - 3.360

4.452 hr/wk

≃ 4.5 hr/wk

Required Maintenance 4.5 hr/wk assume 2/1 ratio mechanical to electrical.

Mechanical: $3.0 \frac{hr}{wk} \times \frac{1}{21} \frac{wk}{shift} \times \frac{1}{8} \frac{shift}{man\text{-}hr} = \underline{\underline{0.0179}}$ person/shift

Electrical: $1.5 \frac{hr}{wk}$ - - - - - - - - - - - - - - - - - $= \underline{\underline{0.00893}}$ person/shift

See note at bottom of page 3

A-20→A-23

Machine produces one 4 $ft^2$ module per minute. Module consists of 1 sheet tempered glass, 3 layers of Craneglas (a mat-type fiberglass) 1 layer clear EVA, 1 layer white EVA, and 1 layer of a polyester-foil laminte back cover. The cell string is obtained in part 6. The polyester/foil was obtained from Gila River Products, Chander, AZ. The cost to us was \$200 for a 1500' x 1' roll (0.13\$/$ft^2$). This was a special price for some surplus material, but is probably a good number for large production quantities.

Expense Item: EMBA01

Name: Polyester/Foil laminate, expressed in $ft^2$

Cost: 0.13 \$/$ft^2$

Base Year: 1981, Inflation Rate: 8

Appendix for Process ROBOTLAY

A-20→A-23

Electricity

Robot = 12.0 KW (mfg. spec.)

Robot 8.00 KW (prorated as per note at bottom of page 3)

| | |
|---|---|
| Stepper motors & valve solenoids | 0.05 KW |
| Computer/controller | 0.10 KW |
| | 8.15 KW →8.15 KWH/hr |

8.15 KWH/hr = 0.136 KWH/min

Compressed air:

Vacuum platen has 35 mini-vac MV-75 eductors each rated at 0.125 cfm

$35 \times 0.125 = 4.375\ ft^3/min.$

Platen operates for 20 sec each 1 min. cycle (This is only the time spent operating at this machine. Time spent at edge seal machine is entered on page 8).

$$4.375\ \frac{ft^3}{min} \times \frac{20\ sec/cycle}{60\ sec/min} = 1.458\ ft^3/cycle$$

$$= 1.458\ ft^3/min\ @\ 1\ min/cycle$$

Six small cylinders use approx. 1 $ft^3/min$

Total air used: $1 + 1.458 = \underline{\underline{2.458\ ft^3/min}}$

Appendix for Process CURE

A-6→A-7

Our approach to the cure cycle involves using 60 modular thermal/vacuum curing chambers interfacing with a single chamber loading/unloading machine (process ROBOTLAY). At present, a one hour cure cycle to evacuate, heat, hold for cure, and cool seems quite feasible (based on current JPL research). See Figure 5-21.

A-8

Based on a 1 min. unload/load cycle, 60 on-line chambers seem to be sufficient for a complete cycle of: 1 min. unload/load, 50 min. evacuate/heat/cool and a 1 min. wait before re-entering the loading machine. This wait allows the change-out of a defective chamber without stopping the line. A one week maintenance of the chamber carrying carousel once a year yields: $\frac{\text{51 wks. up}}{\text{52 wks./yr.}}$

$= \underline{\underline{\text{0.98 up time}}}$

A-11

Purchase Cost:

$1,000 is the estimated cost of a mass produced chamber based on the production costs of the prototype. 60 x $1,000 = $60,000. Another $25,000 is included for the cost of the carousel to carry the chambers, cycle control equipment, power supplies and vacuum pumps.

A-12

Useful Life: 20 yrs. is the life expectancy of the carousel equipment. The chambers are continually refurbished to match this life expectancy (cost covered in maintenance).

A-13

Salvage Value: 5% of purchase cost

A-14

Removal & Installation cost:

As mentioned above in A8, change-out of a defective chamber is considered part of normal operation; therefore, not included here. $5,000 is the estimated removal and installation costs of the carousel and control equipment.

Appendix for Process CURE

A-16→A-19

Manufacturing Space: If the 1 ft. wide chambers are spaced 1 ft. apart, then 60 chambers require (1+1) x 60 = 120 linear ft. of carousel.

A circular carousel with a mean diameter of 40 ft. would do it but the floor area required would be 1520 $ft^2$ based on an outside diameter of 44 ft.

A straight sided, round ended carousel (such as used for luggage at airports) with 35 ft. long sides spaced 16 ft. apart has sufficient length and occupies only 1014 $ft^2$ based on outside dimensions. This still leaves a 12'x35' space in the center for control equipment.

Machine Operator: The operator divides his time between this machine and the lay-up machine in process ROBOTLAY.

Mechanical Maintenance: The one-week maintenance of the carousel once a year requires $\frac{1}{52}$ = 0.0192 person/day

@ 3 shifts/day = $\underline{\underline{0.0064}}$ person/shift

Electrical maintenance - Assume one chamber (essentially an electrical device) per day goes bad requiring an average of 1 hr. to fix

→ 1/24 = 0.0417 person/day

@ 3 shifts/day = $\underline{\underline{0.0139}}$ person/shift

A-20→A-23

Electricity: Each chamber heater is rated at 2.6 KW

1) In each 1 hr. cycle, the heater runs 15 mins. at full power to heat the chamber followed by 20 mins. at half power to maintain cure temperature.

$$15 \text{ min. } (2.6 \text{ KW}) + 20 \text{ min. } (1.3 \text{ KW}) = 65 \frac{\text{KW-min}}{\text{hr}} = 1.0833 \frac{\text{KWH}}{\text{hr}}$$

$$= 0.0181 \frac{\text{KWH}}{\text{min}}$$

$$\text{for 60 chambers} = 1.0833 \frac{\text{KWH}}{\text{min}}$$

2) The 1 HP carousel motor runs for 10 sec. every min. to index the carousel.

$$1 \text{ HP} \times 0.7457 \frac{\text{KW}}{\text{HP}} \times \frac{10}{60} \frac{\text{sec}}{\text{sec/min}} = 0.1243 \frac{\text{KW-min}}{\text{index}} = 0.0021 \frac{\text{KWH}}{\text{index}}$$

$$@ \text{ 1 index/min.} = 0.0021 \frac{\text{KWH}}{\text{min}}$$

Appendix for Process CURE

A-20→A-23

3) A 2 HP vacuum pump, running continuously

$$2\ HP \times 0.7457\ \frac{KW}{HP} = 1.4914\ \ KW \rightarrow 1.4914\ \ \frac{KWH}{Hr} = \underline{\underline{0.0249}}\ \frac{KWH}{min}$$

Total Electricity = 1.0833 + 0.0249 + 0.0021 = $\underline{\underline{1.1103}}$ KWH/Min

Appendix for Process ROBOTSEAL

Background: Our system uses Glass Reinforced Concrete (GRC) panels as a substrate. The panels contain a shallow indentation into which the modules are placed. A bead of hot melt Butyl rubber edge sealant is placed around the module's opening just before the module is put in place by the Unimate robot. (The robot is time shared with process ROBOTLAY as per the note at the bottom of page 3).

The modules can be placed in any configuration up to a maximum size of 4'x8'. The configuration chosen for this simulation is eight 1'x4' placed side by side, joined along the 4 ft side.

A-6→A-7 Rate: The hot melt sealant is extruded at the rate of 2 in/sec. It must be applied to three sides of the module opening: the side common to two modules (in our case the 4 ft dimension) and the two sides along the GRC (the 1 ft sides).

$$\text{Total bead length per module} = (4 \text{ ft} \times 12 \tfrac{\text{in}}{\text{ft}}) + 2\,(1\text{ft} \times 12 \tfrac{\text{in}}{\text{ft}}) = 72 \tfrac{\text{in}}{\text{module}}$$

$$@\ 2 \text{ in/sec} = 36 \text{ sec/module}$$

This fits well with our lamination cycle of 1 min/module allowing a time budget of 5 sec to move the hot melt gun into place, 36 sec to apply the sealant, 5 sec to move the hot melt gun out and 14 sec for robot placement of the module.

One min per module means $\underline{\underline{8 \text{ min/panel}}}$ or $\underline{\underline{1/8 = 0.125 \tfrac{\text{panels}}{\text{min}}}}$

A-8 The hot melt supply spool must be changed (a 30 sec job) every other panel or every 16 min.

$$\text{Up time fraction} = \frac{16 \text{ min up}}{16 + 30/60 \text{ cycle time}} = \underline{\underline{0.97}}$$

Note: Our prototype uses a modified hand-held hot melt applicator which must be reloaded frequently. A true production machine would have remote located heaters and pumps with real-time replenishment which would raise the up time fraction to nearly 100%.

Appendix for Process ROBOTSEAL

Robot:

Unimate 2000B

Purchase Price: $ 49,685. Includes robot base price, additional memory, teach control.

Useful Life: 40,000 hrs. (manufacturer's estimate)

→ 4.83 yrs.

Salvage Value: 50% (manufacturer's estimate) before overhaul

→ $24,842

Installation and Removal Costs: $700 Based on experience with current robot

See note at bottom of page 3

Edge Seal Station:

Purchase cost: Based on development costs of prototype

Useful life: Engineering estimate

Salvage Value: 5% of purchase cost

Removal & Installation Costs: One man week installation time

A-16→A-19

Manufacturing space: Based on prototype machine. Does not include space for robot which is covered in process ROBOTLAY.

Machine Operator: Maneuvering GRC panels (both in and out of machine) and reloading hot melt gun (or tending to a more sophisticated remote pump system) make this station a full time job.

Maintenance:

| | |
|---|---|
| Scheduled - 6.5 hr/1000 hr (mfg. est.) → | 1.092 hr/wk |
| Unscheduled (98% up time) - | 3.360 |
| | 4.452 hr/wk |
| ≃ | 4.5 hr/wk |

Appendix for Process ROBOTSEAL

A-16→A-19

Maintenance (Continued)

Mechanical: $3.0 \frac{hr}{wk} \times \frac{1}{21} \frac{wk}{shift} \times \frac{1}{8} \frac{shift}{man\text{-}hr}$

$= \underline{\underline{0.0179}}$ person/shift

Electrical: $1.5 \frac{hr}{wk}$ - - - - - - - - - - - - -

$= \underline{\underline{0.00893}}$ person/shift

See note at bottom of page 3

A-20→A-23

GRC panel: A 4'x8' panel = 32 $ft^2$

for one panel every 8 min: $\frac{32\ ft^2/panel}{8\ min/panel} = \underline{\underline{4\ ft^2/min}}$

Cost: The GRC panel we are using was developed by MBA for JPL under Contract 955281. The cost for this Expense Item is from the final report for that program, section 7.2

Expense Item: EMBA02
Name: GRC panel expressed in $ft^2$
Cost: 3.69 $\$/ft^2$
Base Year: 1980
Inflation Rate: 10

Butyl Rope: The hot melt supply rope is ¼" diameter and the required bead is 1/8" giving a 2:1 ratio of bead length to supply length.

The relation for total bead length of a panel is:

$L = n(c+2E) + c$ where

n = number of modules in panel
c = length of the module side common to two modules
E = length of the module edge not in common

For this panel L = 8 (4 + 2(1)) + 4 = 52 ft bead

52 ft bead x $\frac{1}{2} \frac{ft\ rope}{ft\ bead}$ = 26 ft rope/panel

@ 8 min/panel = $\underline{\underline{3.25\ ft\ rope/min}}$

Butyl Rope: (Continued)

50 ft Butyl rope supply spools are available in our area for $25 = 0.50 $/ft.

Expense Item: EMBA03
Name: Butyl Rope, expressed in ft.
Cost: 0.50 $/ft.
Base Year: 1981
Inflation Rate: 8

Electricity:

Robot = 12.0 KW (mfgr. spec.)

| | |
|---|---|
| Robot | 4.00 (pro-rated as per note on page 3) |
| Computer/Controller | 0.05 |
| Stepper Motors | 0.025 |
| | 4.075 KW |

→4.075 KWH/Hr = 0.0679 KWH/min

Compressed Air:

Vacuum platen (on robot) has 35 mini-vac MV-75 eductors each rated at 0.125 $ft^3$/min.

35 x 0.125 = 4.375 $ft^3$/min.

Platen operates for 5 second each 1 min. cycle

$$4.375 \frac{ft^3}{min} \times \frac{5 \text{ sec/cycle}}{60 \text{ sec/min}} = 0.3646 \text{ ft}^3\text{/cycle}$$

for 1 min. cycle = 0.3646 $ft^3$/min.

# Appendix B

## Controlling Computer Program Listings

## Computer Program Listings

The following are the listings of the programs used on the TRS-80 computer to control all of the various machi-es in the system.

The first program (starting on page B-2) is used to control the cell stringing machine. It was originally written on the previous contract, although upgraded substantially on this one, and was done in the older "single purpose" style of programming. Its use requires that the assembly language routines (not listed here) be loaded separately under the "SYSTEM" mode.

The second program (page B-4) is for the Laminate Curing Chamber. It was also written in the older "single purpose" style even though it was actually the last to be written. The Therimstor Conversion routine (statements 3000-4010) was purposely written rather long and inefficiently to use up time and hold down the number of loops required in the cure wait.

The last three programs are for the Encapsulant Layup Machine (page B-8), the Edge Sealer for 1'X4' panel (B-12) and the Edge Sealer 2'X4' panel (page B-15). These are written in a newer, modular style of programming which has two important advantages over the older style. First, the same basic "skeleton" is used to operate the valves and/or motors and only the sequence and durations need be changed. Second, the assembly language programming to run the stepper motors is done "real time" from within the BASIC program itself (the odd looking section from 6000 to 9750 in all three programs) eleminating the need for a seperate tape load.

These last three programs are somewhat incomplete as the robot interface had not yet been included at the time of this listing. These interfaces are essentially identicle to the "ROBOT WAIT" and "ROBOT HANDSHAKE" subroutines shown on page B-3, statements 2700-2880.

Finally, with only a slight increase in sophistication, the Edge Sealer programs could be combined and upgraded to a single program which would interrogate the operator as to the size of panel to be made. It would then control the size internally, rather than requiring a separate program for each size panel.

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```
1 REM       CELL STRINGER CONTR... PROGRAM
20 POKE-32765,128:POKE-32768,255:POKE-32767,255:POKE-32766,255:POKE-32761,147:PO
KE-32762,240:POKE16526,224:POKE16527,78
25 A%=47
40 CLS: PRINT'ENTER NUMBER OF CELLS TO BE PREPARED'
90 INPUT F
95 FOR A = 1 TO F
100 CLS:PRINT'PREPARATION OF CELL ';A
102 PRINT'HOME VACUUM CHUCK': GOSUB 2000
104 PRINT'FEED CELL
108 POKE -30,255-16: POKE -31,255-16
112 FOR W=1 TO 125: NEXT W: REM WAIT TO DETERMINE IF LAST CELL
116 C%=PEEK(-32762) AND 12
120 IF C%=8 GOTO 144
124 PRINT@ 473, 'RELOAD SILTEC'
128 FOR W=1 TO 120: NEXT W
132 PRINT@ 473,'              '
136 FOR W=1 TO 70: NEXT W
140 GOTO 116
144 FOR W=1 TO 50: NEXT W: REM WAIT FOR BELT TRAVEL
148 PRINT 'FEED RIBBON'
150 POKE 20466,0:POKE 20471,0: POKE 20472,1: POKE 20474,100: POKE 20476,234: POK
E 20477,1: POKE 20478,213
160 W=USR(0)
170 POKE -31,255: REM STOP SILTEC
180 PRINT'CRIMP'
190 POKE -30,255-128-16: FOR Y = 1 TO 100: NEXT Y
200 POKE -30,255-16: FOR Y = 1 TO 50: NEXT Y
210 PRINT'SHORT RIBBON FEED'
220 POKE 20476,250: POKE 20477,0: W=USR(0)
230 PRINT'CELL SETTLE'
240 FOR Y= 1 TO 424: NEXT Y
250 PRINT'VACUUM TO CHUCK'
260 POKE -30,255-32
265 FOR Y = 1 TO 50: NEXT Y
270 PRINT'ORIENT CELL'
280 GOSUB 2200: GOSUB 2300
290 PRINT'EXTEND CELL SOLDER PASTE DISPENSER'
300 POKE 20466,0: POKE 20471,32: POKE 20472,0: POKE 20474,110:  POKE 20478,208
310 W=USR(0)
320 PRINT'FEED RIBBON WHILE APPLYING SOLDER PASTE'
330 POKE-30,255-32-8
340 POKE 20466,0: POKE 20471,0: POKE 20472,1: POKE 20474,100: POKE 20476,250: PO
KE 20477,1: POKE 20478,213
350 W=USR(0)
360 POKE-30,255-32
370 PRINT'DISPENSE SOLDER PASTE TO CELL'
380 POKE -30,255-32-4
390 FOR Y = 1 TO 127: NEXT Y
400 PRINT'CUT RIBBON.  RETRACT PASTE DISPENSER'
410 POKE -30,255-64-32
420 POKE 20466,0: POKE 20471,16: POKE 20472,0: POKE 20474,110: POKE  20478,213
430 W=USR(0)
435 PRINT'CLAMP RIBBON'
440 POKE-30,255-32-1
450 PRINT'WAIT FOR ROBOT':GOSUB 2700
460 PRINT'HANDSHAKE WITH ROBOT':GOSUB 2800
470 NEXT A
480 GOTO 40
1000 POKE-32761,93
1010 PRINT PEEK(-32762) AND 12
```

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```
1020 GOTO1010
2000 REM HOME VAC CHUCK
2010 POKE20466,0:POKE20471,64:POKE20472,0:POKE20474,80:POKE20478,218
2020 W=USR(0)
2030 RETURN
2200 REM SCAN CELL
2210 POKE20466,255:POKE20467,255:POKE20468,255:POKE20471,0
2220 POKE20472,0:POKE20474,20:POKE20476,32:POKE20477,3:POKE20478,218
2230 W=USR(0)
2240 RETURN
2300 REM ALIGN CELL
2305 A%=120
2310 V%=PEEK(20469)+PEEK(20470)*256-5
2360 U%=V%+A%:POKE20478,223
2365 IFU%=0GOTO2395
2370 T=U%/256:U1%=INT(T):U2%=(T-U1%)*256
2375 POKE20476,U2%:POKE20477,U1%
2380 POKE20466,0:POKE20472,0:POKE20474,100
2390 W=USR(0)
2395 RETURN
2700 REM WAIT FOR  ROBOT
2710 K%=PEEK(-32762)AND1
2720 IF K%<>0 GOTO 2710
2730 RETURN
2800 REM HANDSHAKE WITH ROBOT
2805 FORY=1TO 500:NEXTY
2810 POKE-32767,255-64:FORY=1TO100:NEXTY:POKE-32767,255
2820 K%=PEEK(-32762)AND2
2830 IF K%<>0 GOTO 2820
2840 POKE-32766,255:FORY=1TO200:NEXTY
2850 POKE-32767,255-64:FORY=1TO500:NEXTY:POKE-32767,255
2860 K%=PEEK(-32762)AND2
2870 IF K%=0 GOTO 2860
2880 RETURN
2999 REM CELL ALLIGNMENT TEST ROUTINE
3000 GOSUB2200:GOSUB2300
3005 FORY=1TO500:NEXTY
3010 V%=RND(0)*800:GOSUB2360
3015 FORY=1TO10:NEXTY
3020 GOTO3000
4999 REM LIMIT SWITCH TEST ROUTINE
5000 POKE-32762,255-128:CLS
5010 POKE-32762,255
5020 LETK%=PEEK(-32763)AND128
5030 IFK%<>0 GOTO5020
5040 PRINT(PEEK(-32763)AND15)*16[2+PEEK(-32764)
5050 GOTO5000
7000 REM VALVE TEST ROUTINE
7005 INPUT V
7010 POKE -30,255-V
7015 PRINT V
7020 INPUT D
7030 POKE -30,255INP
7040 GOTO 7005
```

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```
10  REM       CURING CHAMBER CONTROL PROGRAM
100 POKE-12285,128
110 POKE-12288,255
120 POKE-12287,255
130 POKE-12286,255
230 POKE-12281,147
600 CLS
610 PRINT@465,'START VACUUM PUMP.  PRESS 'ENTER''
620 INPUT D
999 REM SETUP DATA DISPLAY
1000 CLS
1005 PRINT:PRINT:PRINT:PRINT:PRINT
1010 PRINT TAB(25) 'SYSTEM STATUS'
1015 PRINT
1020 PRINT TAB(3) 'PHASE'; TAB(14)'TEMPERATURE'; TAB(31)'HEATER'; TAB(44)'VACUUM
'; TAB(57)'VALVE'
1030 GOSUB 3000
1040 PRINT@545,'OFF'
1045 REM   BEGIN PUMPDOWN CYCLE
1050 PRINT@514,'PUMPDOWN'
1060 FOR V=1 TO 30
1070 FOR D=1 TO 150
1080 GOSUB 2500
1120 IF V1>V THEN GOTO 1160
1130 POKE -12286,255-16
1140 PRINT@569,' OPEN  '
1150 GOTO  1180
1160 POKE -12286,255
1170 PRINT@569,'CLOSED'
1180 NEXT D
1190 NEXT  V
1195 REM  BEGIN CHAMBER HEATING TO CURE TEMPERATURE
1200 PRINT@514,'  HEAT  '
1210 POKE -12286,255-28
1220 PRINT@545,'ON  '
1230 GOSUB 3000
1235 GOSUB 2500
1240 IF T1<300 THEN GOTO 1230
1270 REM  BEGIN CURE WAIT AT TEMPERATURE
1280 PRINT@516,'CURE'
1290 FOR T= 1 TO 4000
1320 GOSUB 3000
1325 GOSUB 2500
1330 IF T1>=300 THEN GOTO  1370
1340 POKE -12286,255-28
1350 PRINT@545,'ON '
1360 GOTO 1390
1370 POKE -12286,255-16
1380 PRINT@545,'OFF'
1390 NEXT T
1395 REM    BEGIN COOLDOWN TO 150 F
1400 PRINT@514,'COOLDOWN'
1410 POKE -12286,255-16
1420 PRINT@545,'OFF'
1450 GOSUB 3000
1455 GOSUB 2500
1460 IF T1> 150 THEN GOTO 1450
1463  REM   BLEED CHAMBER TO AMBIENT
```

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```
1465 PRINT@512,'CHAMBER VENT'
1470 POKE -12286,255
1480 PRINT@569,'CLOSED'
1490 GOSUB 2500
1500 IF V1>0  THEN GOTO 1490
1510 PRINT@512,'   DONE       '
1520 GOSUB  2500
1530 GOSUB  3000
1540 GOTO 1520
2499 REM VACUUM TRANSDUCER CONVERSION ROUTINE
2500 POKE-12281,11:POKE-12281,9
2510 GOSUB  60100
2520 V1=INT(30*(H+L-1216)/2457)
2530 PRINT@557,V1
2540 RETURN
2999 REM THERMISTOR CONVERSION ROUTINE
3000 POKE-12281,10:POKE-12281,8
3003 GOSUB 60100
3007 A=H+L
3010 IF A>0 THEN 3040
3020 T1=-140
3030 GOTO 4000
3040 IF A>15 THEN 3070
3050 T1= 145
3060 GOTO 4000
3070 IF A>50  THEN 3100
3080 T1=150
3090 GOTO 4000
3100 IF A>65 THEN 3130
3110 T1= 155
3120 GOTO 4000
3130 IF A>125 THEN 3160
3140 T1= 160
3150 GOTO 4000
3160 IF A>140 THEN 3190
3170 T1=165
3180 GOTO 4000
3190 IF A>190 THEN 3220
3200 T1=170
3210 GOTO 4000
3220 IF A>220 THEN 3250
3230 T1=175
3240 GOTO 4000
3250  IF A>255  THEN  3280
3260 T1=180
3270 GOTO4000
3280 IF  A>280  THEN 3310
3290 T1=185
3300 GOTO4000
3310 IF A>320 THEN 3340
3320 T1=190
3330 GOTO  4000
3340 IF A>365 THEN 3370
3350 T1=195
3360 GOTO 4000
3370 IF A>380 THEN 3400
3380 T1=200
3390 GOTO 4000
3400 IF A>480  THEN 3430
3410 T1=205
3420 GOTO4000
3430 IF A>510 THEN 3460
3440 T1=210
3450 GOTO4000
3460 IF A>575 THEN 3490
3470 T1=215
```

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```
3480 GOTO4000
3490 IF  A>630 THEN 3520
3500 T1=220
3510 GOTO 4000
3520 IF A>700 THEN 3550
3530 T1=225
3540 GOTO 4000
3550 IF A>770 THEN 3580
3560 T1=230
3570 GOTO  4000
3580 IF A>830 THEN 3610
3590 T1=235
3600 GOTO 4000
3610 IF A>900 THEN 3640
3620 T1=240
3630 GOTO  4000
3640 IF A>960 THEN 3670
3650 T1= 245
3660 GOTO 4000
3670 IF A>1020 THEN 3700
3680 T1=250
3690 GOTO4000
3700 IF A>1055 THEN 3730
3710 T1=255
3720 GOTO 4000
3730 IF A>1215  THEN 3760
3740 T1=260
3750 GOTO 4000
3760 IF A>1270 THEN 3790
3770 T1=265
3780 GOTO 4000
3790 IF A>1310 THEN 3820
3800 T1=270
3810 GOTO 4000
3820 IF A>1440 THEN 3850
3830 T1=275
3840 GOTO 4000
3850 IF A>1500 THEN 3860
3860 T1=280
3870 GOTO 4000
3880 IF A>1600 THEN 3910
3890 T1=285
3900 GOTO 4000
3910 IF A>1650 THEN 3940
3920 T1=290
3930 GOTO 4000
3940 IF A>1675 THEN 3955
3945 T1=295
3950 GOTO 4000
3955 IF A>1700 THEN 3970
3960 T1=300
3965 GOTO 4000
3970 IF A>1730 THEN 3985
3975 T1=305
3980 GOTO4000
3985 IF A>1790 THEN 4000
3990 T1=310
4000 PRINT@529,T1
4010 RETURN
11000 REM INDIVIDUAL FUNCTION RUN ROUTINE
11001 PRINT"INPUT VALVE OR HEATER CODE":  INPUT X
11002 IFX=128THENGOTO11015
11005 POKE-12287,255
11007 POKE-12286,255-X
11010 GOTO11000
11015 POKE-12287,255-128
```

```
11020 GOTO11000
59999 REM  SENSOR READ ROUTINE
60000 FORI=-12284TO-12281
60010 PRINTPEEK(I)
60015 NEXTI
60016 PRINT
60020 FORK=1TO400
60030 NEXTK
60050 GOTO60000
60100 POKE-12281,14
60110 POKE-12281,15
60120 LETL=PEEK(-12284)
60130 LETH=PEEK(-12283)
60140 LETH=HAND15
60150 LETH=H*256
60160 RETURN
60500 GOSUB60100
60510 GOTO60500
61000 POKE-12281,14:POKE-12281,15:GOTO61000
```

```
10 REM       LAYUP MACHINE CONTROL PROGRAM
100 POKE-12285,128
110 POKE-12288,255
120 POKE-12287,255
130 POKE-12286,255
135  REM   SETUP ASSEMBLY LANGUAGE ROUTINES
140 DATA1,0,0,33,240,127,126,183,202,3,127,35
145 DATA50,0,0,17,0,0
150 DATA122,179,27,194,18,127,120,177,11,194,6,127,201
155 DATA 58,5,208,238,0,230,16,194,6,127,201
160 FORM=32512TO32553
170 READ B
180 POKE M,B
190 NEXT M
200 POKE16526,0
210 POKE16527,127
220 GOSUB9000
230 POKE-12281,147
1000 STOP
4999 REM  MANUAL MOTOR RUN ROUTINE
5000 PRINT"INPUT MOTOR NUMBER";:INPUTM
5010 PRINT"INPUT STEP RATE";:INPUTR
5020 PRINT"INPUT STEP COUNT";:INPUTS
5022 PRINT"INPUT DIRECTION 1,-1";:INPUTD
5025 GOSUB6000
5030 GOSUB 9500
5040 GOSUB 9600
5050 GOSUB 9700
5060 LETZ1=USR(0)
5070 GOTO5000
6000 REM SETS UP DIR AND MOTOR TABLE
6010 IFM=1THENGOTO6100
6020 IFD=1THENGOSUB9000
6030 IFD-1THENGOSUB9070
6040 RETURN
6100 REM SETS UP MOTOR 1
6105 IFD=1THENGOSUB8000
6110 IFD=-1THENGOSUB8100
6120 RETURN
8000 POKE32752,95
8010 POKE32753,111
8020 POKE32754,175
8030 POKE32755,159
8040 POKE32756,0
8050 RETURN
8100 POKE32752,159
8110 POKE32753,175
8120 POKE32754,111
8130 POKE32755,95
8140 POKE32756,0
8150 RETURN
9000 REM SET TABLE FOR CCW
9010 POKE32752,255-10
9020 POKE32753,255-9
9030 POKE32754,255-5
9040 POKE32755,255-6
9050 POKE32756,0
9060 RETURN
```

```
9070 REM SET TABLE FOR CW MOTORS #1 & #3
9080 POKE32752,255-6
9090 POKE32753,255-5
9100 POKE32754,255-9
9110 POKE32755,255-10
9120 POKE32756,0
9130 RETURN
9500 REM SET UP NUMBER OF STEPS
9520 LETS1=INT(S/256)
9530 POKE32514,S1
9540 LETS2=S-S1*256
9550 POKE32513,S2
9560 RETURN
9600 REM SET  UP MOTOR ADDRESS
9610 IFM=1THENPOKE32525,0:POKE32526,208
9620 IFM=2THENPOKE32525,0:POKE32526,208
9630 IFM=3THENPOKE32525,1:POKE32526,208
9640 RETURN
9700 REM SET UP STEP RATE
9710 LETR1=INT(R/256)
9720 POKE32529,R1
9730 LETR2=R-R1*256
9740 POKE32528,R2
9750 RETURN
11000 REM  MANUAL VALVE OPERATION ROUTINE
11001 PRINT'INPUT VALVE NUMBER': INPUT X
11002 IFX=128THENGOTO11015
11005 POKE-12287,255
11007 POKE-12286,255-X
11010 GOTO11000
11015 POKE-12287,255-128
11020 GOTO11000
12000 IFX=128THENGOTO12050
12010 POKE-12287,255
12020 POKE-12286,255-X
12030 RETURN
12050 POKE-12287,255-X
12060 RETURN
12070 INPUTX
12080 GOSUB12000
12090 GOTO12070
13000 REM SYSTEM RUN ROUTINE
13002 PRINT'MOTOR =';M
13003 PRINT'RATE  =';R
13004 PRINT'STEPS =';S
13005 PRINT'DIRECTION =';D
13006 PRINT'VALVE  =';X
13007 PRINT'DELAY =';T
13010 GOSUB6000
13020 GOSUB9500
13030 GOSUB9600
13040 GOSUB9700
13050 LETZ1=USR(0)
13060 RETURN
15000 PRINT'CYCLE START'
15010 M=3:S=20000:R=250:D=-1
15020 GOSUB50200
15030 GOSUB13000
15040 GOSUB50100
15050 M=2:S=10:R=700:D=-1:X=6:
15060 GOSUB12000
15070 GOSUB13000
15080 S=215:T=200:D=1
15090 GOSUB12000
15100 GOSUB20000
15110 GOSUB13000
```

```
15120 T=200
15130 GOSUB20000
15140 T=200:X=38
15150 GOSUB12000
15160 GOSUB20000
15170 M=3:R=250:S=8800:D=1:T=200:X=50
15180 GOSUB50300
15190 GOSUB12000
15200 GOSUB20000
15210 GOSUB13000
15220 X=38:T=200:M=2:R=700:D=-1:S=15
15230 GOSUB12000
15240 GOSUB20000
15250 GOSUB13000
15260 T=400
15270 POKE-12287,255-128
15280 GOSUB20000
15290 GOSUB12000
15300 T=200
15310 GOSUB20000
15320 M=3:S=1150:R=250:D=1:X=6
15330 GOSUB13000
15340 GOSUB12000
15350 S=2000:GOSUB50300
15360 POKE32549,32
15370 GOSUB13000
15380 GOSUB50100
15500 M=1:D=-1:S=10:R=700:X=6:T=300
15510 GOSUB12000
15520 GOSUB20000
15530 GOSUB13000
15540 D=1:S=215
15550 GOSUB13000
15560 T=200
15570 GOSUB20000
15580 T=200:X=38
15590 GOSUB12000
15600 GOSUB20000
15610 M=3:R=250:D=-1:S=8800:X=44:T=200
15620 GOSUB12000
15630 GOSUB20000
15640 GOSUB13000
15650 X=38:M=1:D=-1:R=700:S=13:T=200
15660 GOSUB12000
15670 GOSUB20000
15680 GOSUB13000
15690 T=400
15700 POKE-12286,255-33
15710 GOSUB20000
15720 GOSUB12000
15730 T=200
15740 GOSUB20000
15750 M=3:S=1150:D=-1:R=250:X=6
15760 GOSUB13000
15770 GOSUB12000
15780 S=1000:GOSUB50200
15790 GOSUB13000
15800 GOSUB50100
15810 M=3:R=250:X=6:D=1:T=300:S=20000
15815 GOSUB50300
15820 GOSUB12000
15830 GOSUB20000
15840 GOSUB13000
15850 GOSUB50100
15860 POKE-12288,255:POKE-12287,255:POKE-12286,255
15870 STOP
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
20000 FORT1=1TOT
20010 NEXTT1
20020 RETURN
40000 PRINTPEEK(-12284)
40010 PRINTPEEK(-12283)
40020 PRINTPEEK(-12282)
40022 FORI=1TO300:NEXTI
40025 PRINT
40030 GOTO40000
50000 POKE32539,200:POKE32540,0:POKE32541,0:POKE32542,0
50010 RETURN
50100 POKE32539,194:POKE32540,6:POKE32541,127:POKE32542,201
50110 RETURN
50200 GOSUB50000
50210 POKE32549,16
50220 RETURN
50300 GOSUB50000
50310 POKE32549,32
50320 RETURN
50400 GOSUB50000
50410 POKE32549,64
50420 RETURN
50500 GOSUB50000
50510 POKE32544,6:POKE32549,1
50520 RETURN
60000 FORI=-12284TO-12281
60010 PRINTPEEK(I)
60015 NEXTI
60016 PRINT
60020 FORK=1TO400
60030 NEXTK
60050 GOTO60000
60100 POKE-12281,14
60110 POKE-12281,15
60120 LETL=PEEK(-12284)
60130 LETH=PEEK(-12283)
60140 LETH=HAND15
60150 LETH=H*256
60160 RETURN
60500 GOSUB60100
60510 GOTO60500
61000 POKE-12281,14:POKE-12281,15:GOTO61000
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
   10 REM   EDGE SEALER CONTROL ROUTINE FOR 1X4 PANEL
100 POKE-12285,128
110 POKE-12288,255
120 POKE-12287,255
130 POKE-12286,255
140 DATA1,0,0,33,240,127,126,183,202,3,127,35
145 DATA50,0,0,17,0,0
150 DATA122,179,27,194,18,127,120,177,11,194,6,127,201
155 DATA 58,5,208,238,0,230,16,194,6,127,201
160 FORM=32512TO32553
170 READ B
180 POKE M,B
190 NEXT M
200 POKE16526,0
210 POKE16527,127
220 GOSUB9000
230 POKE-12281,147
1000 STOP
5000 PRINT"INPUT MOTOR NUMBER";:INPUTM
5010 PRINT"INPUT STEP RATE";:INPUTR
5020 PRINT"INPUT STEP COUNT";:INPUTS
5022 PRINT"INPUT DIRECTION 1,-1";:INPUTD
5025 GOSUB6000
5030 GOSUB 9500
5040 GOSUB 9600
5050 GOSUB 9700
5060 LETZ1=USR(0)
5070 GOTO5000
6000 REM SETS UP DIR AND MOTOR TABLE
6010 IFM=1THENGOTO6100
6020 IFD=1THENGOSUB9000
6030 IFD-1THENGOSUB9070
6040 RETURN
6100 REM SETS UP MOTOR 1
6105 IFD=1THENGOSUB8000
6110 IFD=-1THENGOSUB8100
6120 RETURN
8000 POKE32752,95
8010 POKE32753,111
8020 POKE32754,175
8030 POKE32755,159
8040 POKE32756,0
8050 RETURN
8100 POKE32752,159
8110 POKE32753,175
8120 POKE32754,111
8130 POKE32755,95
8140 POKE32756,0
8150 RETURN
9000 REM SET TABLE FOR CCW
9010 POKE32752,255-10
9020 POKE32753,255-9
9030 POKE32754,255-5
9040 POKE32755,255-6
9050 POKE32756,0
9060 RETURN
9070 REM SET TABLE FOR CW MOTORS #1 & #3
9080 POKE32752,255-6
9090 POKE32753,255-5
```

```
9100 POKE32754,255-9
9110 POKE32755,255-10
9120 POKE32756,0
9130 RETURN
9500 REM SET UP NUMBER OF STEPS
9520 LETS1=INT(S/256)
9530 POKE32514,S1
9540 LETS2=S-S1*256
9550 POKE32513,S2
9560 RETURN
9600 REM SET  UP MOTOR ADDRESS
9610 IFM=1THENPOKE32525,0:POKE32526,208
9620 IFM=2THENPOKE32525,0:POKE32526,208
9630 IFM=3THENPOKE32525,1:POKE32526,208
9640 RETURN
9700 REM SET UP STEP RATE
9710 LETR1=INT(R/256)
9720 POKE32529,R1
9730 LETR2=R-R1*256
9740 POKE32528,R2
9750 RETURN
11000 PRINT"INPUT VALVE POSITION";:INPUTX
11002 IFX=128THENGOTO11015
11005 POKE-12287,255
11007 POKE-12286,255-X
11010 GOTO11000
11015 POKE-12287,255-128
11020 GOTO11000
12000 IFX=128THENGOTO12050
12010 POKE-12287,255
12020 POKE-12286,255-X
12030 RETURN
12050 POKE-12287,255-X
12060 RETURN
12070 INPUTX
12080 GOSUB12000
12090 GOTO12070
13000 REM SYSTEM RUN ROUTINE
13002 PRINT"MOTOR =";M
13003 PRINT"RATE  =";R
13004 PRINT"STEPS =";S
13005 PRINT"DIRECTION =";D
13006 PRINT"VALVE  =";X
13007 PRINT"DELAY =";T
13010 GOSUB6000
13020 GOSUB9500
13030 GOSUB9600
13040 GOSUB9700
13050 LETZ1=USR(0)
13060 RETURN
15000 PRINT"CYCLE  START"
15004 GOSUB50200
15010 M=3:R=1000:D=-1:S=10000:X=128
15020 GOSUB12000
15030 GOSUB13000
15032 GOSUB50100
15033 GOSUB50400
15035 M=2:R=1000:S=10000:D=-1:X=128
15040 GOSUB12000
15050 GOSUB13000
15060 T=50000
15070 X=128
15080 GOSUB50100
15090 GOSUB12000
15100 GOSUB20000
15110 M=3:R=1000:D=1:S=194:X=128:T=200
```

```
15112 GOSUB20000
15115 X=128
15120 GOSUB13000
15130 GOSUB12000
15135 S=336:X=129
15150 GOSUB12000
15155 GOSUB13000
15160 M=2:R=1000:D=1:S
=1370:X=129
15170 GOSUB12000
15180 GOSUB13000
20000 FORT1=1TOT
20010 NEXTT1
20020 RETURN
40000 PRINTPEEK(-12284)
40010 PRINTPEEK(-12283)
40020 PRINTPEEK(-12282)
40022 FORI=1TO300:NEXTI
40025 PRINT
40030 GOTO40000
50000 POKE32539,200:POKE32540,0:POKE32541,0:POKE32542,0
50010 RETURN
50100 POKE32539,194:POKE32540,6:POKE32541,127:POKE32542,201
50110 RETURN
50200 GOSUB50000
50210 POKE32549,16
50220 RETURN
50300 GOSUB50000
50310 POKE32549,32
50320 RETURN
50400 GOSUB50000
50410 POKE32549,64
50420 RETURN
50500 GOSUB50000
50510 POKE32544,6:POKE32549,1
50520 RETURN
60000 FORI=-12284TO-12281
60010 PRINTPEEK(I)
60015 NEXTI
60016 PRINT
60020 FORK=1TO400
60030 NEXTK
60050 GOTO60000
60100 POKE-12281,14
60110 POKE-12281,15
60120 LETL=PEEK(-12284)
60130 LETH=PEEK(-12283)
60140 LETH=HAND15
60150 LETH=H*256
60160 RETURN
60500 GOSUB60100
60510 GOTO60500
61000 POKE-12281,14:POKE-12281,15:GOTO61000
```

```
        10 REM EDGE SEALER  CONTROL ROUTINE FOR 2X4 PANEL
100 POKE-12285,128
110 POKE-12288,255
120 POKE-12287,255
130 POKE-12286,255
140 DATA1,0,0,33,240,127,126,183,202,3,127,35
145 DATA50,0,0,17,0,0
150 DATA122,179,27,194,18,127,120,177,11,194,6,127,201
155 DATA 58,5,208,238,0,230,16,194,6,127,201
160 FORM=32512TO32553
170 READ B
180 POKE M,B
190 NEXT M
200 POKE16526,0
210 POKE16527,127
220 GOSUB9000
230 POKE-12281,147
1000 STOP
5000 PRINT"INPUT MOTOR NUMBER";:INPUTM
5010 PRINT"INPUT STEP RATE";:INPUTR
5020 PRINT"INPUT STEP COUNT";:INPUTS
5022 PRINT"INPUT DIRECTION 1,-1";:INPUTD
5025 GOSUB6000
5030 GOSUB 9500
5040 GOSUB 9600
5050 GOSUB 9700
5060 LETZ1=USR(0)
5070 GOTO5000
6000 REM SETS UP DIR AND MOTOR TABLE
6010 IFM=1THENGOTO6100
6020 IFD=1THENGOSUB9000
6030 IFD-1THENGOSUB9070
6040 RETURN
6100 REM SETS UP MOTOR 1
6105 IFD=1THENGOSUB8000
6110 IFD=-1THENGOSUB8100
6120 RETURN
8000 POKE32752,95
8010 POKE32753,111
8020 POKE32754,175
8030 POKE32755,159
8040 POKE32756,0
8050 RETURN
8100 POKE32752,159
8110 POKE32753,175
8120 POKE32754,111
8130 POKE32755,95
8140 POKE32756,0
8150 RETURN
9000 REM SET TABLE FOR CCW
9010 POKE32752,255-10
9020 POKE32753,255-9
9030 POKE32754,255-5
9040 POKE32755,255-6
9050 POKE32756,0
9060 RETURN
9070 REM SET TABLE FOR CW MOTORS #1 & #3
9080 POKE32752,255-6
9090 POKE32753,255-5
9100 POKE32754 255-9
```

```
9110 POKE32755,255-10
9120 POKE32756,0
9130 RETURN
9500 REM SET UP NUMBER OF STEPS
9520 LETS1=INT(S/256)
9530 POKE32514,S1
9540 LETS2=S-S1*256
9550 POKE32513,S2
9560 RETURN
9600 REM SET  UP MOTOR ADDRESS
9610 IFM=1THENPOKE32525,0:POKE32526,208
9620 IFM=2THENPOKE32525,0:POKE32526,208
9630 IFM=3THENPOKE32525,1:POKE32526,208
9640 RETURN
9700 REM SET UP STEP RATE
9710 LETR1=INT(R/256)
9720 POKE32529,R1
9730 LETR2=R-R1*256
9740 POKE32528,R2
9750 RETURN
11000 PRINT"INPUT VALVE POSITION";:INPUTX
11002 IFX=128THENGOTO11015
11005 POKE-12287,255
11007 POKE-12286,255-X
11010 GOTO11000
11015 POKE-12287,255-128
11020 GOTO11000
12000 IFX=128THENGOTO12050
12010 POKE-12287,255
12020 POKE-12286,255-X
12030 RETURN
12050 POKE-12287,255-X
12060 RETURN
12070 INPUTX
12080 GOSUB12000
12090 GOTO12070
13000 REM SYSTEM RUN ROUTINE
13002 PRINT"MOTOR =";M
13003 PRINT"RATE  =";R
13004 PRINT"STEPS =";S
13005 PRINT"DIRECTION =";D
13006 PRINT"VALVE  =";X
13007 PRINT"DELAY =";T
13010 GOSUB6000
13020 GOSUB9500
13030 GOSUB9600
13040 GOSUB9700
13050 LETZ1=USR(0)
13060 RETURN
15000 PRINT"CYCLE  START"
15004 GOSUB50200
15010 M=3:R=1000:D=-1:S=10000:X=2
15020 GOSUB12000
15030 GOSUB13000
15032 GOSUB50100
15033 GOSUB50400
15035 M=2:R=1000:S=10000:D=-1:X=2
15040 GOSUB12000
15050 GOSUB13000
15060 T=50000
15080 GOSUB50100
15100 GOSUB20000
15110 M=3:R=1000:D=1:S=194:X=2:T=200
15112 GOSUB20000
15120 GOSUB13000
15130 GOSUB12000
```

```
15135 S=336:X=3:T=200:R=1500
15140 GOSUB20000
15150 GOSUB12000
15155 GOSUB13000
15160 M=2:R=1500:D=1:S
=1370:X=3:T=35
15170 GOSUB12000
15175 GOSUB20000
15180 GOSUB13000
15200 M=3:S=343:D=-1:R=1500:X=3:T=30
15205 GOSUB50200
15210 GOSUB12000
15220 GOSUB20000
15230 GOSUB13000
15235 GOSUB50400
15240 M=2:D=-1:R=1500:S=1370:X=3:T=50
15250 GOSUB12000
15260 GOSUB20000
15270 GOSUB13000
15280 GOSUB50100
15285 POKE-12287,255:POKE-12288,2:55:POKE-12286,255
15290 STOP
15300 GOSUB50300
15310 M=3:D=1:R=1000:S=2000:X=2:T=200
15320 GOSUB12000
15330 GOSUB20000
15340 GOSUB13000
15350 GOSUB50100
15360 STOP
15400 M=3:D=-1:R=1000:S=1663:X=2:T=200
15410 GOSUB12000
15420 GOSUB20000
15430 GOSUB13000
15440 X=3:S=336:D=1:R=1500:T=200
15450 GOSUB12000
15460 GOSUB20000
15470 GOSUB13000
15480 M=2:R=1500:S=1370:D=1:X=3:T=100
15490 GOSUB12000
15500 GOSUB20000
15510 GOSUB13000
15520 M=3:S=336:D=-1:R=1500:X=3:T=100
15530 GOSUB12000
15540 GOSUB20000
15550 GOSUB13000
15560 M=2:R=1500:S=1370:D=-1:X=3:T=100
15570 GOSUB12000
15580 GOSUB20000
15590 GOSUB13000
15600 M=3:S=1000:D=1:R=1000:X=2:T=200
15610 GOSUB12000
15620 GOSUB20000
15630 GOSUB13000
15640 STOP
16000 PRINT"CYCLE START"
16010 GOSUB50200
16020 M=3:R=1000:S=20000:D=-1:X=2:T=200
16030 GOSUB12000
16040 GOSUB20000
16050 GOSUB13000
16060 GOSUB50100
16070 GOSUB50400
16080 M=2:S=20000:D=-1:R=1000:X=2:T=200
16090 GOSUB12000
16100 GOSUB20000
16110 GOSUB13000
```

```
16120 GOSUB50100
16130 T=30000
16140 GOSUB20000
16150 M=3:R=1000:D=1:S=539:X=2
16160 GOSUB12000
16170 GOSUB13000
16180 X=3:R=2000:S=344:D=-1:T=200
16190 GOSUB12000
16200 GOSUB20000
16210 GOSUB13000
16215 GOSUB50500
16220 T=200:X=3:D=1:M=2:S=1378:R=2000
16230 GOSUB12000
16240 GOSUB20000
16250 GOSUB13000
16255 GOSUB50100
16260 M=3:R=2000:S=344:D=1:X=3:T=100
16270 GOSUB12000
16280 GOSUB20000
16290 GOSUB13000
16300 X=2:S=2000:R=1000:T=200
16310 GOSUB12000
16320 GOSUB20000
16330 GOSUB13000
16335 GOSUB50100
16340 STOP
16350 M=3:R=1000:S=1657:D=-1:X=2:T=200
16360 GOSUB12000
16370 GOSUB20000
16380 GOSUB13000
16390 X=3:T=200:R=2000:S=347:M=3
16400 GOSUB12000
16410 GOSUB20000
16420 GOSUB13000
16430 M=2:S=1378:R=2000:D=-1:X=3:T=100
16440 GOSUB12000
16445 GOSUB50400
16450 GOSUB20000
16460 GOSUB13000
16465 GOSUB50100
16470 M=3:R=2000:D=1:S=347:X=3:T=100
16480 GOSUB12000
16490 GOSUB20000
16500 GOSUB13000
16505 GOSUB50500
16510 M=2:S=1378:D=1:R=2000:X=3:T=100
16520 GOSUB12000
16530 GOSUB20000
16540 GOSUB13000
16545 GOSUB50100
16546 POKE-12288,255:POKE-122877,255:POKE-12286,255
16550 STOP
20000 FORT1=1TOT
20010 NEXTT1
20020 RETURN
40000 PRINTPEEK(-12284)
40010 PRINTPEEK(-12283)
40020 PRINTPEEK(-12282)
40022 FORI=1TO300:NEXTI
40025 PRINT
40030 GCTO40000
50000 POKE32539,200:POKE32540,0:POKE32541,0:POKE32542,0
50010 RETURN
50100 POKE32539,194:POKE32540,6:POKE32541,127:POKE32542,201
50110 RETURN
50200 GOSUB50000
```

ORIGINAL P...
OF POOR Q...

```
50210 POKE32549,16
50220 RETURN
50300 GOSUB50000
50310 POKE32549,32
50320 RETURN
50400 GOSUB50000
50410 POKE32549,64
50420 RETURN
50500 GOSUB50000
50510 POKE32544,6:POKE32549,1
50520 RETURN
60000 FORI=-12284TO-12281
60010 PRINTPEEK(I)
60015 NEXTI
60016 PRINT
60020 FORK=1TO400
60030 NEXTK
60050 GOTO60000
60100 POKE-12281,14
60110 POKE-12281,15
60120 LETL=PEEK(-12284)
60130 LETH=PEEK(-12283)
60140 LETH=HAND15
60150 LETH=H*256
60160 RETURN
60500 GOSUB60100
60510 GOTO60500
61000 POKE-12281,14:POKE-12281,15:GOTO61000
```

## Appendix C

## Acknowledgments and Addresses

The author would like to thank the following individuals and organizations for their help in the performance of this program:

Dublin Radio Shack, Scott Williams (manager)
7112 Dublin Blvd., Dublin, CA 94566 (415) 828-7820
Computer equipment and services

ARCO Solar, Inc., Dr. Charles Gay
20554 Plummer St., Chatsworth, CA 91311 (213) 700-7152
Solar cells and interconnect material

Gila River Products, William Bell
6615 W. Boston St., Chandler, AZ 85224 (602) 961-1244
Multi-ply foil lamination materials

Springborn Laboratories, Paul Willis
Water St., Enfield, CT 06082 (203) 749-8371
EVA materials and cure cycle spec.

J. M. Leaver Co., James Leaver
2409 Old Crow Canyon Rd., San Ramon, CA 94583 (415) 820-5828
Glass Reinforced Concrete materials and fabrication

Crystal Mark Inc., Mark Wynar
613 Justin Ave., Glendale, CA 91201 (213) 240-7520
Custom System Enclosure

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Other suppliers of equipment and materials:

Unimation Inc.
Shelter Rock Ln., Danbury CT 06810 (203) 744-1800
Robotic equipment and information

Electrolock Inc.
16838 Park Circle, Chagrin Falls, OH 44022 (216) 543-5125
Craneglas material

Tridak Div., Indicon Inc.
Secor Rd., Brookfield Center, CT 06805 (203) 775-1287
Solder paste dispensing systems

EFD Inc.
977 Waterman Ave., East Providence, RI 02914 (401) 434-1680
Solder Paste

# Appendix D

# Encapsulation Cure Cycle

ENCAPSULATION CURE CYCLE

As mentioned in Section 7.2.3, the cure cycle used is a combination of information supplied by Springborn Labs and Spectrolab Inc., combined with the results of our own experiences.

The cycle starts with a gradual, controlled pumpdown of the chamber to avoid cell cracking; an inherent problem with single chamber vacuum bags. The slope of the pumpdown curve is 3 in-Hg/min. requiring, therefore, 10 minutes to pump the chamber from ambient to a perfect 30 in-Hg vacuum. Because of pump limitations, and imperfect cover sealing, the actual chamber pressure begins to deviate from the commanded level at about 23 in-Hg, as shown in Figure 7-3. Although the computer keeps commanding lower and lower pressures for the full 10 minutes, actual chamber pressures level out at between 26-27 in-Hg.

After the pumpdown phase is completed, the heater is turned on to heat the chamber, at its maximum rise rate, to 300$^{\circ}$F. Although this is shown as taking 10 minutes on the graph (Figure 7-3) in our system, the rise time was closer to 20 minutes.

Once at the proper level, the temperature is maintained, $\pm 2^{\circ}$F, by the control system for 30 minutes. This is the curing time specified for this temperature by Springborn Labs.

When the curing time has clocked out, the heater is turned off and chamber is allowed to cool to 150$^{\circ}$F. We used a small muffin fan to ventilate the enclosed underside of the chamber framework to help speed the step. There is no specified rate for the cooldown and could presumably be as fast as the thermal characteristics of the glass and other materials will allow without causing damage. The 15 minutes shown on the figure for this phase reflects the use of the ventilating fan; without it, the time is approximately 20-25 minutes.

Once the panel temperature drops below $150^{\circ}F$, the vacuum solenoid is closed and the chamber allowed to return to ambient pressure through natural leakage. Due to the chamber's very small free volume (only the 1/4" space around the perimeter of the module) this venting process takes less than one minute.

After the chamber pressure reaches ambient, the computer prints "DONE" on the screen in the "PHASE" column to indicate that processing is complete. However, it continues to display the panel temperature for as long as desired, until shut off.